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FLOW OF GAS-SOLID MIXTURES IN VERTICAL CIRCULAR PIPES,
I: CALIBRATION AND USE OF [illegible] DEVICES

by

E. [illegible]

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE IN CHEMICAL ENGINEERING

DEPARTMENT OF CHEMICAL AND PETROLEUM ENGINEERING

EDMONTON, ALBERTA
OCTOBER, [illegible]

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1964
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THE UNIVERSITY OF ALBERTA

FLOW OF GAS-SOLID MIXTURES IN VERTICAL CIRCULAR DUCTS, I: CALIBRATION AND USE OF AIR VELOCITY MEASURING DEVICES

by

B. BOWERS

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
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ABSTRACT

The design of equipment and preliminary investigations for a study of the flow of gas-solid mixtures in a vertical circular duct are presented in this thesis. The object of this initial phase of the study was to design equipment for the investigations and to establish calibrations and experimental techniques for the measurement of point velocity within the duct.

A hot-wire anemometer (model HWB2) was purchased from Flow Corporation for use in the studies. Two standard straight stem hot-wire probes were supplied with this instrument. In addition a probe designed specifically for the measurement of velocity profiles in the duct was obtained. Another velocity sensing device, a hot-film probe, was purchased for evaluation.

A small scale copy of the British standard pitot-static tube was constructed. This instrument was used to investigate and establish the calibration curves for the hot-wire and hot-film probes in the air velocity range 5 to 13 feet per second. Below 5 feet per second the calibration of a hot-wire probe was established by a trial and error procedure to obtain the best agreement between flow rates measured by means of an orifice and those obtained by the integration of velocity profiles. This instrument was then used in the calibration of the other hot-wire probe and the hot-film probe in the low velocity range.

Velocity profiles in the circular duct were measured using the pitot-static tube, the hot-wire probe and the hot-film probe, covering the Reynolds number range 900 to 31,000 in the test section. The form of the fully developed turbulent profiles was compared with form obtained by previous investigators.

It was concluded that King's formula describes the form of calibration curves for the hot-wire probes. At air velocities greater than 5 feet per second, the error in mean velocity measurement is larger with the hot-wire than with the pitot-static tube. The hot-wire probe is superior to the hot-film probe for use in air containing no suspended solid. The equipment described allows the study of fully developed turbulent profiles in the range of Reynolds number 17,000 to 31,000, the results obtainable being comparable to those obtained by previous investigators.

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I. INTRODUCTION

Frequently in industry the suspension and transport of a friable solid in a carrier gas will facilitate an operation or process. Evidence of this is found in the growing popularity of pneumatic transport installations, driers utilizing pneumatic transport and the increasing number of processes which rely on a gas-suspended solid catalyst. Engineers engaged in the design of equipment for these operations must be able to predict the rate of solids transport, solids dispersion and pressure drop involved in the transport. These predictions could be made more reliable if a greater knowledge and more fundamental understanding of the nature of the flow of gas-solid mixtures were available. It is towards this end that the present work is directed. In particular the aspect of vertical transport is to be investigated.

The presence of a suspended solid in a gas flow manifests itself in the rules for velocity distribution of the flow and for pressure drop estimation. An experimental program designed to study fully the phenomena occuring in the flow would involve studies of axial and radial diffusion, velocity profiles and patterns of particle hold-up. An obvious prerequisite of such a program is a means of measuring point velocity and it was with this initial phase that the present work was concerned. The main object of this work was to assess the available methods for the measurement of air velocity profiles in a circular duct in the absence of solids. In subsequent studies, the extension of these results to gas-solids flows will be considered.

In the past the pitot-static tube, the total-head tube and the hot-wire anemometer have been used extensively in the measurement of velocity profiles. More recently the hot-film probe has been developed and this

instrument would seem to be applicable in streams containing suspended solids.

The Total-Head and Pitot-Static Tubes.

The total-head and pitot-static tubes are the simplest, most rugged, and reliable instruments for the measurement of mean point velocity above a velocity of about 3 feet per second. They have the further advantage that a single calibration endures throughout the life of the instrument. Mechanical damage which is easily detected is the only cause for a calibration change. For this reason the pitot-static tube in particular is frequently used as a standard against which other instruments are calibrated.

The total-head tube simply consists of a tube with a right angle bend. The tube opening is directed upstream so that the pressure within the tube is the total pressure. This pressure, measured by a suitable manometer, when corrected for static pressure, gives a measure of the fluid velocity. The pitot-static tube is made up of a total head tube inside a static tube (see figure 10). The manometer directly measures the dynamic or impact pressure ΔP which is related to the velocity U in the case of an incompressible fluid or when the dynamic pressure is very small by the equation:

$$U = \sqrt{\frac{2Kg_c \, \Delta P}{\rho}} \quad \text{\_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_} \quad (1)$$

The value of the calibration constant K for a given instrument must be determined by calibration.

In the lower velocity range (below about 3 feet per second) the application of the pitot-static and total-head tubes is limited on account of the difficulty encountered in measuring the small dynamic pressure involved.

Micromanometers have been designed to extend the range of accurate velocity measurement in the lower velocity region. Such a micromanometer was available for the present study.

A further short-coming of these instruments is due to the fact that the tube opening must be of finite size, and the point velocity of the fluid will vary across it. Usually the measured velocity is considered to be at the centre of the tube opening. This is true if point velocities are being measured in the central portion of the stream where the velocity gradient is small. Close to a boundary, however, the velocity gradient may be large and in such a case it can be shown theoretically that this is no longer true (4). This problem has been minimized by using total head tubes with very small openings, of the order of 0.001 inches (5, 6, 7).

The Hot-Wire and Hot-Film Anemometers.

Since the development of the necessary electronic accessory equipment the hot-wire anemometer has been used extensively in aerodynamic research work. The instrument consists essentially of an electrically heated platinum or tungsten resistance wire mounted between two steel needles. The size of the wire ordinarily used ranges from 0.0001 to 0.001 inches in diameter and 0.02 to 0.5 inches in length. The heat loss from the wire to the flowing air stream equals the heat generated in it by virtue of its electrical resistance. This loss is a function of air speed, air direction, air properties, dimensions of the wire and air-wire temperature difference.

King (8) derived and experimentally verified at low speeds the relationship used to express the forced convective heat loss from fine wires with axes normal to the flow. In the range of air speed 10 to 180 feet per second where air velocity U is usually the only independent variable it is

customary for a particular instrument to express this relationship in the form of a linear calibration curve (9, 10, 11, 12, 26).

The heat generated in the wire is I^2R_w, where I is the wire heating current and R_w the wire resistance. Accordingly, there are basically two techniques of hot wire operation. These are known as the constant resistance and constant current techniques. In the case of the former, the heating current required to maintain a definite wire resistance is the measure of the air cooling effect, while in the latter the resistance attained by the wire with a constant current flowing through it is the measure. A modification of the constant resistance method, known as the constant resistance ratio method, is employed by the Flow Corporation Model HWB2 Hot-wire Anemometer which was used in the present work. In this technique, the ratio of the resistance of the heated wire to the resistance of the wire at substantially stream temperature is maintained at a known value. The heating current required to achieve this known resistance ratio is a measure of the air cooling effect. It is claimed (16) that this method of operation eliminates any effect of air stream temperature or wire aging from the measurement. The form of the linear relationship in this case is (15, 16):

$$I^2 = A\sqrt{PU} + B \qquad (2)$$

Recent studies (10, 11, 12, 14) have shown that King's relationship does not correctly express the forced convective heat loss from fine wires in the range of velocity where air compressibility must be considered. However, the present work is concerned with very low velocity flows (less than 15 feet per second).

The hot-wire anemometer is preferred rather than the pitot-static tube when sensitive measurement at a point is required and when very low velocities are to be measured. The small size of the wire which may be used enables measurements to be made without disturbing the air flow and close to surfaces. In turbulence investigations the hot-wire has proven to be a very useful tool and it is in this area that it finds its widest application.

Due to the mechanical delicacy of the hot-wire the instrument is unsuitable for the measurement of velocity in flows containing suspended solids. Impact of solids on the wire may cause breakage and also solids may adhere to the wire decreasing the sensitivity of the instrument.

A new type of sensing element operating in a similar manner to the hot-wire but with better mechanical properties has recently been developed (25). This element consists of a very thin platinum film fused on to the tip of a wedge shaped glass probe. The glass acts as a support for the film which accounts for the superior mechanical properties. It is reported (25) that this form of probe minimizes the collection of solids from the fluid stream and provides a more efficient and uniform heat-transfer surface so that the small amount of dirt which does collect has less effect on the rate of heat transfer.

II. LITERATURE REVIEW

The review was undertaken with the object of obtaining background information concerning the use of the pitot-static tube and the hot-wire in the measurement of mean point velocity at low air speeds. Correlations of velocity profile data in a circular duct obtained by others were included in the review for comparison with those obtained in the present study.

The Total-Head and Pitot-Static Tubes.

The pitot-static tube and its operation are well known. Of particular interest in the present study were those references giving a detailed description of the mechanical design of pitot-tubes along with a detailed evaluation of the calibration constants for the instruments (1, 2, 29). Bramwell et al. (1) describe the design and calibration of a pitot-static tube that was later adopted as the British standard. The range of their investigation of the calibration was 20 to 60 feet per second. Later work by Ower and Johansen (2) covered the range 2 to 20 feet per second for the standard size tube and also for a small scale copy of the standard. Another form of pitot-static tube designed to have a calibration constant of unity above 20 feet per second, has also received considerable attention (29, 2). It has a hemispherical nose and is known as a Prandtl tube (30). This instrument was used by van Zoonen (3) in his gas-solid flow studies.

Laufer (7) used a total-head tube with flattened opening 0.006 inches wide to measure mean velocity profiles, except in his higher Reynolds number profile where he used a hot-wire close to the wall. Rothfus et al. (6) used a total-head tube having an opening 0.0015 by 0.024 inches while Deissler (5) used a total-head having an opening 0.0005 inches diameter.

Laufer (7) considered it necessary to correct his mean velocities obtained with the total-head tube for the effect of velocity fluctuations due to turbulence in the vicinity of the pipe wall. The correction was of the order of 5 percent or less and had the form:

$$U_{corr} = U\sqrt{1 - \frac{\overline{u^2} + \overline{v^2} + \overline{w^2}}{U^2}} \approx U\sqrt{1 - \frac{\overline{u^2}}{U^2}} \quad \text{\_ \_ \_ \_ \_ \_ \_ \_ \_ (3)}$$

Hot-Wire Anemometry.

It was found that much of the published literature on hot-wire anemometry deals with the use of the instrument for turbulence investigation and its adaption to use at transonic and supersonic air speeds. The problem of mean velocity measurement at low speeds is encountered less frequently. The subject of hot-wire anemometry has been comprehensively reviewed by Willis (9). Detailed discussions of the mechanical arrangements of hot-wires and their use are given by Lowell (10) and by Laurence and Landes (21), while the electronic accessory equipment required is described by Kovasznay (26).

The work of King (8) forms the basis for the use of the hot-wire for the measurement of mean velocity. The equation he obtained to express the relationship between the rate of heat loss and the air velocity for a wire with its axis normal to the direction of flow was:

$$\frac{H}{T_w - T} = f_1\sqrt{U} + f_2 \quad \text{\_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ \_ (4)}$$

The relationship was experimentally verified by King himself over the range of air velocity 1 to 20 feet per second and was later confirmed by others (12, 13, 14). At higher air speeds where compressibility must be considered,

departure from the relationship was observed by Lowell (10) and others (11, 12, 14). Sandborn (12) mentions that deviation from King's linear relationship was observed at a velocity of 180 feet per second and greater.

As pointed out by King (8) there is also a lower limit to relationship 4. He deduced theoretically that this lower limit can be determined from a critical value of Ud given by $Ud = 2.01 \times 10^{-5}$ feet^2 per second, where d is the diameter of the wire. Weske (14) states that the lower limit occurs at a value of Reynolds number, based upon wire diameter, of 0.108 for air at standard atmospheric conditions. These statements are important in that they conflict with the statement made in Flow Corporation Bulletins 25 and 37B (15, 16) that King's linear relationship can be extrapolated to zero velocity for the geometry of hot-wire filaments supplied on Flow Corporation probes.

The temperature dependence of the functions f_1 and f_2 was examined by King (8). His findings were that the variation of f_1 was little greater than the variation due to experimental errors, while the variation of f_2 could be expressed by an equation of the form:

$$f_2 = C_2 + C_3 (T_w - T) \quad \text{-------------} \quad (5)$$

where C_2 and C_3 are constants for a given wire. These findings were confirmed in 1951 by Corrsin and Uberoi (27, 28).

Numerous investigators (12, 13, 17, 18) have calibrated the hot-wire against a pitot-static or total head tube. Sandborn (12) used two techniques for calibrating a hot-wire against a total-head probe. In one procedure the wire was placed at the pipe centre line and its response recorded at various mass flow rates which were evaluated by means of the total-head probe. In the other procedure, which he calls a "continuous calibration", the wire response was recorded at various radii in the pipe.

Values of mean velocity at these radii were then obtained from the mean velocity profile obtained by independent measurements with the total-head probe. Sandborn used the continuous calibration procedure in his turbulence investigation. The turbulence measurements were recorded as the calibration curve was being generated, thus minimizing errors due to erratic calibration changes.

A crude calibration technique is described in Flow Corporation Bulletins 25 and 37B (15, 16) which it is claimed will allow measurement of mean velocity with an error of ± 5 percent. The technique requires that the response of the wire be measured in still air and at one known velocity. The calibration curve is assumed to be linear between the two points thus obtained. A more accurate calibration curve (± 2 percent error in mean velocity) can be generated by using more known velocity points.

Practically every user of the hot-wire anemometer has been troubled by erratic calibration changes (19). Willis (9) mentions that calibration constants may vary appreciably from week to week and that the normal procedure is to calibrate the wire at least at the beginning and end of each measuring day. Quoting from Dryden and Kuethe (13) who used a platinum wire of 0.017 inches diameter: "The calibration curve was subject to erratic changes of the same type as those described by Bailey and Simmons (22) for a wire of 0.025 mm. diameter but even more troublesome. In spite of calibrations two and four times per day and of numerous returns to a reference point during a traverse, it was difficult to secure an accuracy of better than ± 1.5 percent in the mean speed." An error of up to 10 percent in mean velocity may result from erratic changes in calibration according to Sandborn (12).

Schubauer (19) concludes that a change in the relative humidity of the air is one factor which causes a change in the calibration. He found that a change in the relative humidity from 25 to 75 percent for air at 25°C and atmospheric pressure resulted in an error in mean speed measurement of about 6 percent. Sandborn (12) suggests that dust particles in the stream cause these discontinuous changes in the calibration curve. Spangenberg (11) also found that room dust carried by the air stream accumulated on the wire which had considerable effect on the response of the wire. It is mentioned in Flow Corporation literature (15, 16) also that the calibration curve of a solid-laden wire is not linear and has poorer velocity resolution than that for a clean wire.

Lowell (10) briefly discusses the design and use of wires so as to minimize the effect of the impact of solid particles. He suggests the use of relatively large diameter wires constructed of material having a high yield point in tension. Inclination of the wire to the direction of flow also aids in reducing impact effects.

Despite the difficulties encountered in the use of the hot-wire anemometer it has been used for studies in which mean velocity profiles are measured. Sleicher (18) used platinum (0.00016 ins. diameter) and tungsten wires for this purpose. In his studies the wire was frequently calibrated against a pitot-static tube at the centre of the pipe. By this procedure the accuracy of mean velocity measurements was ±0.5 percent at moderate velocities decreasing to ±5 percent at 7 feet per second. Other studies in which the hot-wire anemometer has been used for the study of mean velocity profiles include those by Laufer (23), Corcoran et al. (17) and Weissberg

and Berman (20). Laufer (23) used platinum wires, one centimeter in length and 0.0005 inches diameter. Corcoran et al. (17) also used 0.0005 inches diameter platinum but with a length of 0.38 inches. Weissberg and Berman (20) used tungsten wires 0.00012 inches in diameter and 0.02 to 0.05 inches in length. The calibration procedures used and accuracies obtained in these works were similar to those of Sleicher (18).

Laufer (7, 23) applied a correction to his mean velocities measured with the hot-wire to account for the error in measurement due to air turbulence. The relationship between the mean velocity as measured by the hot-wire and true mean velocity he used was (23):

$$U_w = U\left[1 - \left(\frac{3}{16}\right)\left(\frac{\overline{u^2}}{U^2}\right)\right] \tag{6}$$

The maximum correction applied to the velocity measured with the hot-wire occurred near the wall and was about 10 percent, the correct mean velocity being higher than the observed (7).

Correlations of Velocity Profile Data for Circular Ducts.

The methods of correlating velocity profile data can be found reviewed in standard texts on fluid mechanics (4, 30, 31). Prandtl, as reported by Knudsen and Katz (4), conducted a very extensive study of turbulent velocity profiles in a circular duct. From the Blasius friction factor equation for the flow of fluids in tubes he derived a preliminary relationship for velocity profiles for the case of turbulent pipe flow. This relationship is (4, 30):

$$\frac{U}{U_m} = C\left(\frac{y}{R}\right)^{\frac{1}{7}} \tag{7}$$

and is known as the power law for the velocity distribution in turbulent flow. It is valid for the range of Reynolds number over which the Blasius friction factor equation is applicable, namely 21,000 to 100,000.

A more frequently used method of correlating velocity profile data is by means of the universal velocity distribution equations for turbulent flow in circular tubes. For the whole cross section of the circular tube the following three relationships express the velocity distribution (4):

Laminar layer:

$$\frac{U}{U_*} = \frac{y\,U_*\,\rho}{\mu} \qquad \text{where} \quad \frac{y\,U_*\,\rho}{\mu} < 5 \quad \text{--- (8a}$$

Buffer layer:

$$\frac{U}{U_*} = -3.05 + 5.0 \ln \frac{y\,U_*\,\rho}{\mu} \qquad \text{where} \quad 5 < \frac{y\,U_*\,\rho}{\mu} < 30 \quad \text{--- (8b}$$

Turbulent core:

$$\frac{U}{U_*} = 5.5 + 2.5 \ln \frac{y\,U_*\,\rho}{\mu} \qquad \text{where} \quad \frac{y\,U_*\,\rho}{\mu} > 30 \quad \text{--- (8c}$$

In this thesis the turbulent core only is studied. The values of the constants in equation (8c), namely 5.5 and 2.5, were obtained by Nikuradse as reported by Knudsen and Katz (4). Deissler (24) obtained the values 3.8 and 2.78 respectively.

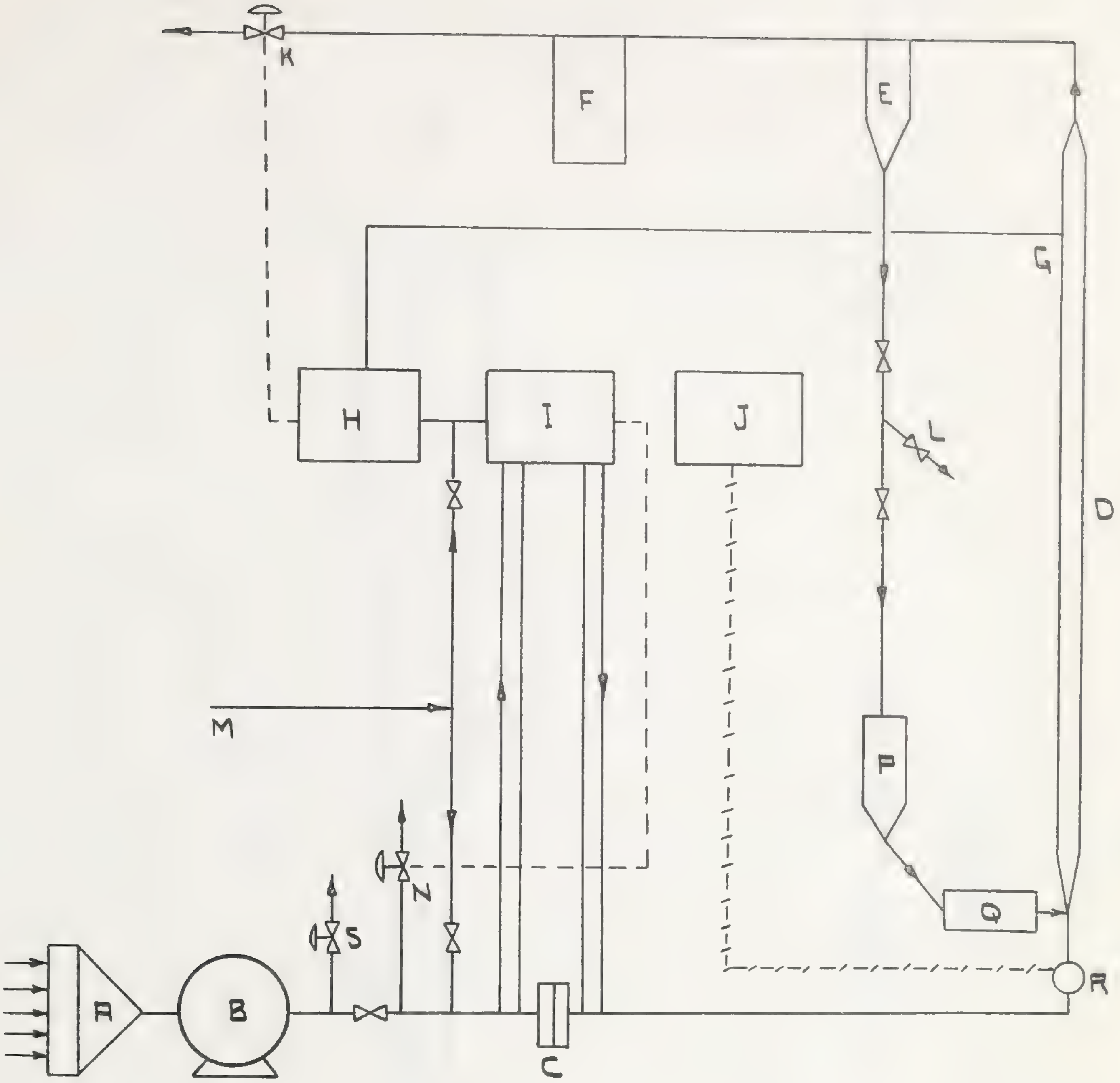
III. EXPERIMENTAL EQUIPMENT

The Test Pipe.

The equipment, illustrated by a line diagram in figure 1, was designed to study the flow of gas-solid mixtures over a Reynolds number range of 1,000 - 30,000 in the test section. An aluminium tube of relatively large inside diameter (6.255 inches) was selected for the study in order to improve accuracy of probe location measurement and to reduce any effect due to the roughness of the walls of the tube to a minimum. A length of 31.5 feet of this tube was installed in a vertical position in the research well. The vertical orientation was checked by means of a transit.

Air was introduced to the test pipe through a venturi having a throat diameter of one inch. The design of this venturi is shown in figure 2. Provision was made for the introduction of solids at the throat. Air exhausted from the test pipe through a transition and long radius bend of 2.067 inches internal diameter, designed to reduce turbulence effects at the exit. The design of the exit transition is shown in figure 3.

The main profile measurement section was located 30.33 feet from the throat of the entrance venturi. Further profile measurement locations were included at distances of 5, 9 and 14 feet upstream of the main location. These were designed for the purpose of studying at a later date the development of the velocity profiles and determining the range of Reynolds number over which stable and fully developed profiles could be obtained at the main location.



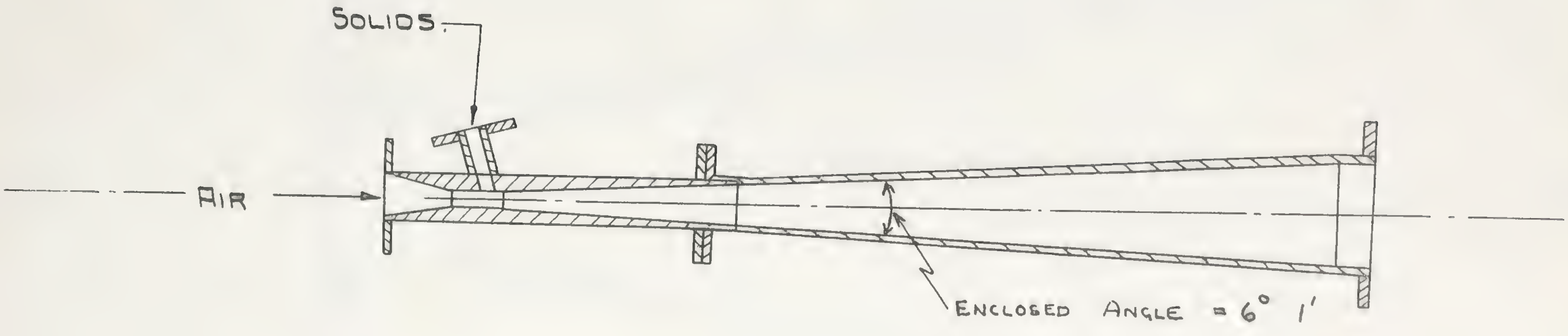
A	Air Intake Filter
B	Blower
C	Orifice Plate
D	Test Pipe
E	Cyclone Separator
F	Bag Filter
G	Static Pressure Tap.
H	Pressure Recorder-Controller
I	Air-Weight Recorder-Controller
J	Temperature Recorder
K	Back Pressure Valve

Key:-

Flow Line	————
Control Line	- - - -
Electrical Line	-/-/-/-

L	Solids Sampling Tap
M	Compressed Air Source
N	Bleed Off Valve
P	Solids Container
Q	Screw Feeder
R	Thermocouple
S	Pressure Relief Valve

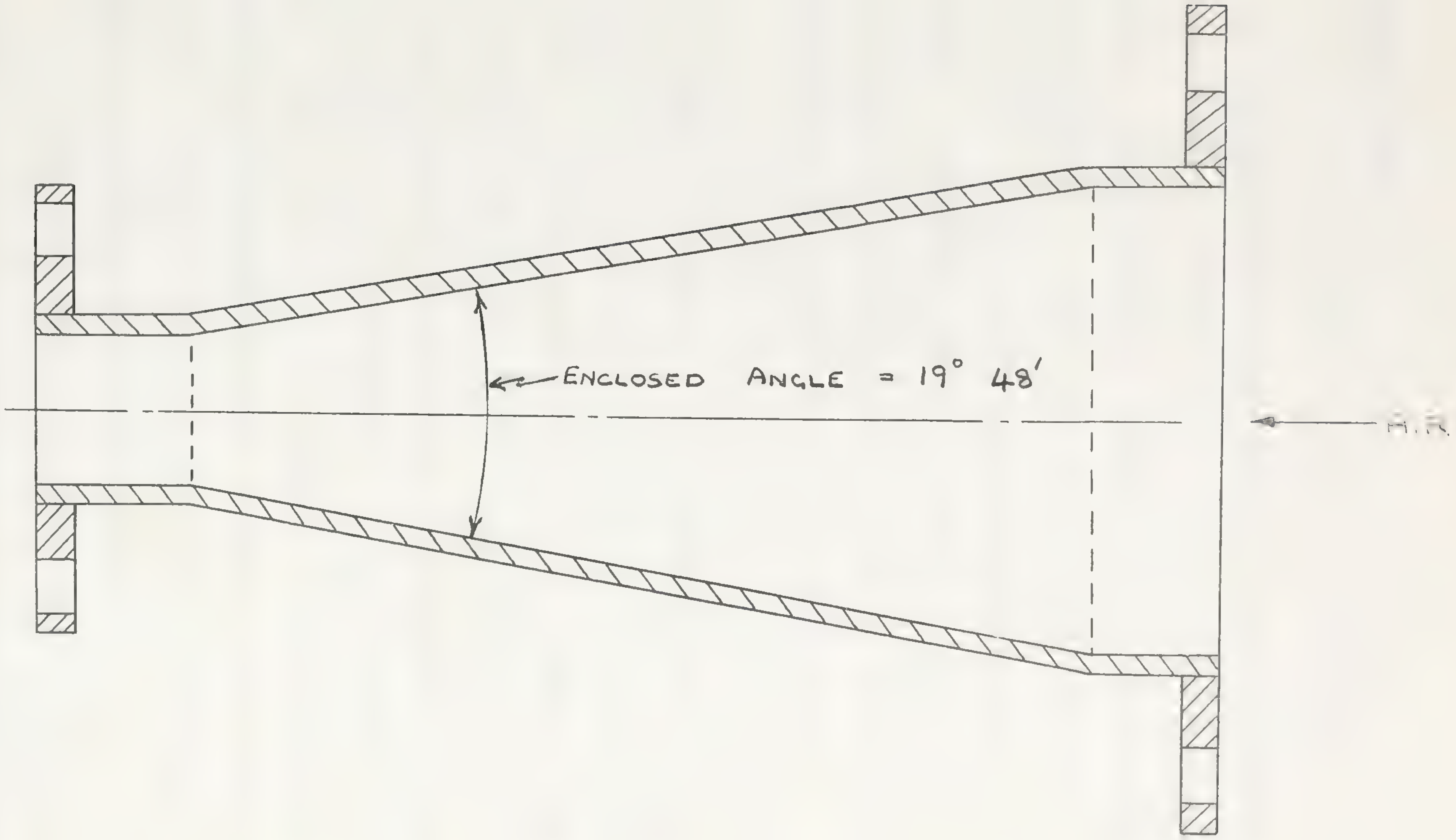
Figure 1. Line Diagram Of Equipment.



ENTRANCE VENTURI.

FIGURE 2.

SCALE: 1/10 FULL SIZE.
THROAT DIA. = 1 INCH.



EXIT TRANSITION.

SCALE: 4/10 FULL SIZE.

FIGURE 3.

The Air System.

The air intake was located in the basement of the research well. The air was filtered by glass fibre filters and supplied to the test pipe by means of a Roots-Connersville type AF rotary positive displacement blower. The blower, size number 36, had a rated capacity of 134 cubic feet per minute at 1750 r.p.m. with a total differential of 2 p.s.i. across the blower. Power for the blower was supplied by a 2 h.p., General Electric, three phase, induction motor. Rated speed of the motor was 1735 r.p.m. and it was fitted with a Reeves varispeed pulley, so that the blower speed could be controlled independently.

The air mass flow rate was controlled by means of a Foxboro M40 air weight controller. The primary element for this instrument consisted of a sharp-edged orifice of 1.544 inches diameter installed in 300 lb. standard $2\frac{1}{2}$-inch steel orifice flanges (Ladish). Entrance and exit sections of the orifice meter run were designed according to the specifications of the American Gas Association (32) and consisted of 6 feet and $2\frac{1}{2}$ feet respectively of $2\frac{1}{2}$ inch schedule 40 galvanized iron pipe. The 3 to 15 p.s.i.g. output air signal from the air weight controller pneumatically operated a $1\frac{1}{4}$ inch parabolic needle valve (Foxboro type F-8) acting as a bleed-off valve on the system and by means of which the required mass flow rate was maintained.

The absolute pressure at the test section in the test pipe was designed to be controlled by means of a Foxboro M40 stabilog controller. The input to the controller was from a static pressure tap located in the test pipe, while the output, consisting of a 3 to 15 p.s.i.g. air signal,

pneumatically operated 2 inch parabolic needle valve (Foxboro type F - 8) acting as a back pressure valve on the system.

Temperature of the air was measured just prior to its introduction to the entrance venturi by means of a thermocouple in combination with a Brown single-point temperature recorder.

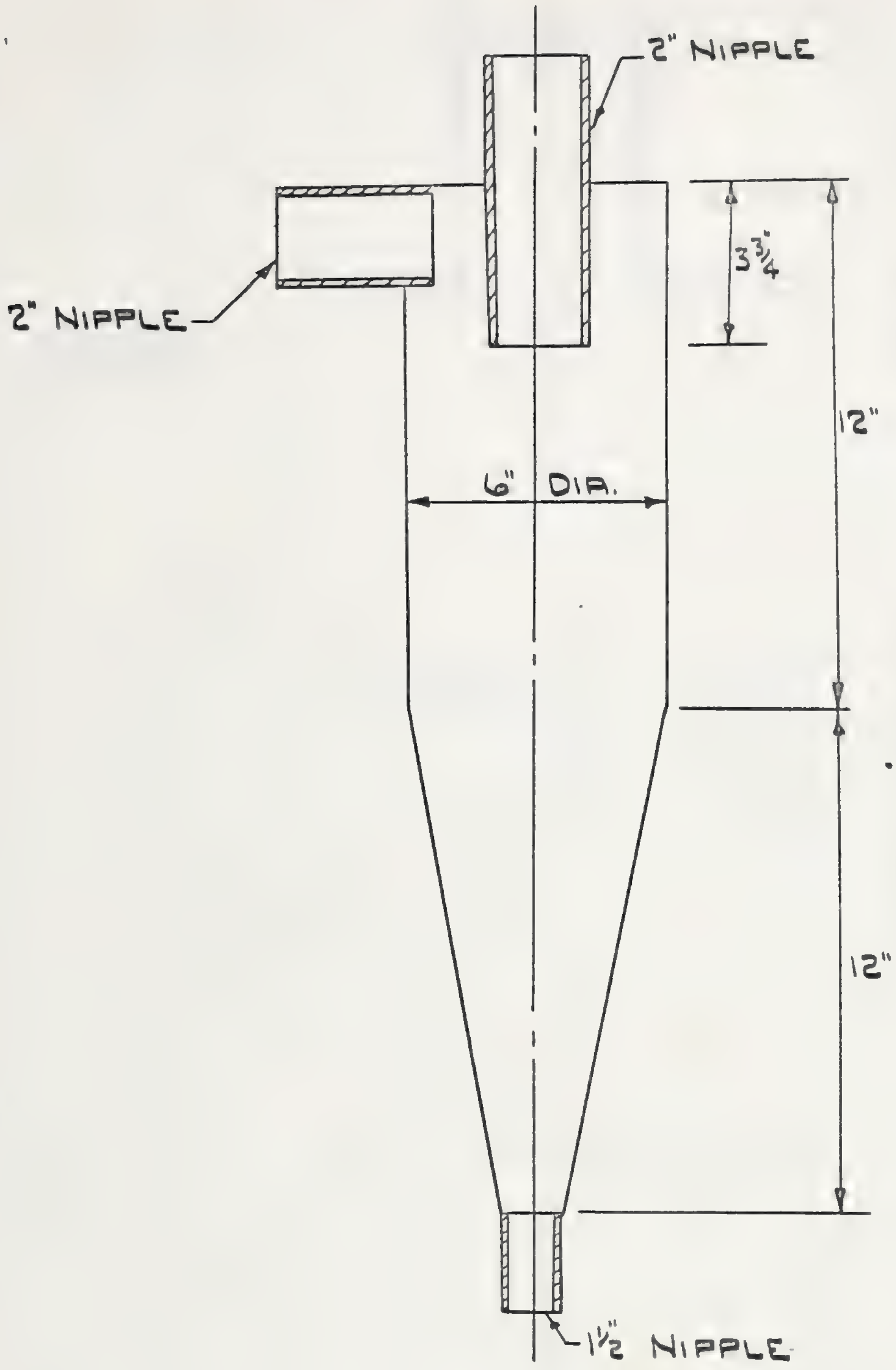
The Solids System.

Although no experimental work involving the flow of solids in the air stream was undertaken, provision was included for the introduction of the solids at the throat of the entrance venturi. Extraction of the solids was to be made by means of cyclone separator and bag filter situated just prior to the discharge of the air through the back pressure valve. These items were constructed of 16 gauge sheet metal and their designs are shown in figures 4 and 5. A solids return line of one inch schedule 40 galvanized iron pipe was installed to carry solids from the bottom of the cyclone separator back to the solids container. The design of the latter is given in figure 6. A tap by means of which the solids could be extracted or sampled was included in the return line.

The Traversing Mechanism.

A traversing mechanism was constructed by Mr. R. Kirby to permit location of probes in relation to the wall of the pipe and to guide probes diametrically across the pipe. The mechanism is shown in figure 7 with a probe in position. It consisted essentially of two pipe clamps carrying a support of "L" shaped cross-section on which the probe slide was mounted.

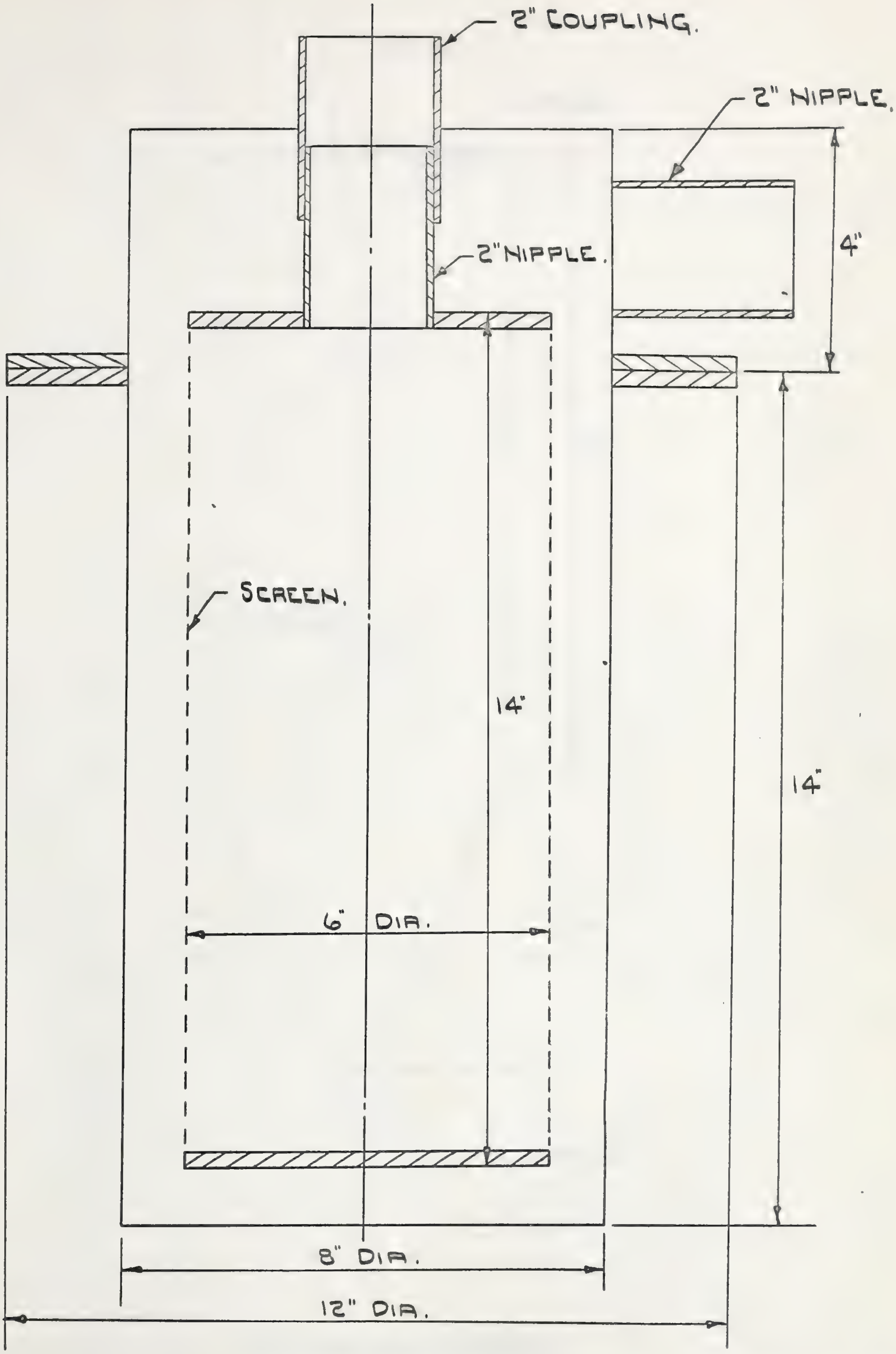
Design was such that when the mechanism was mounted on the pipe, a probe, clamped in the slide block, would automatically lie in a diametric



CYCLONE SEPARATOR.

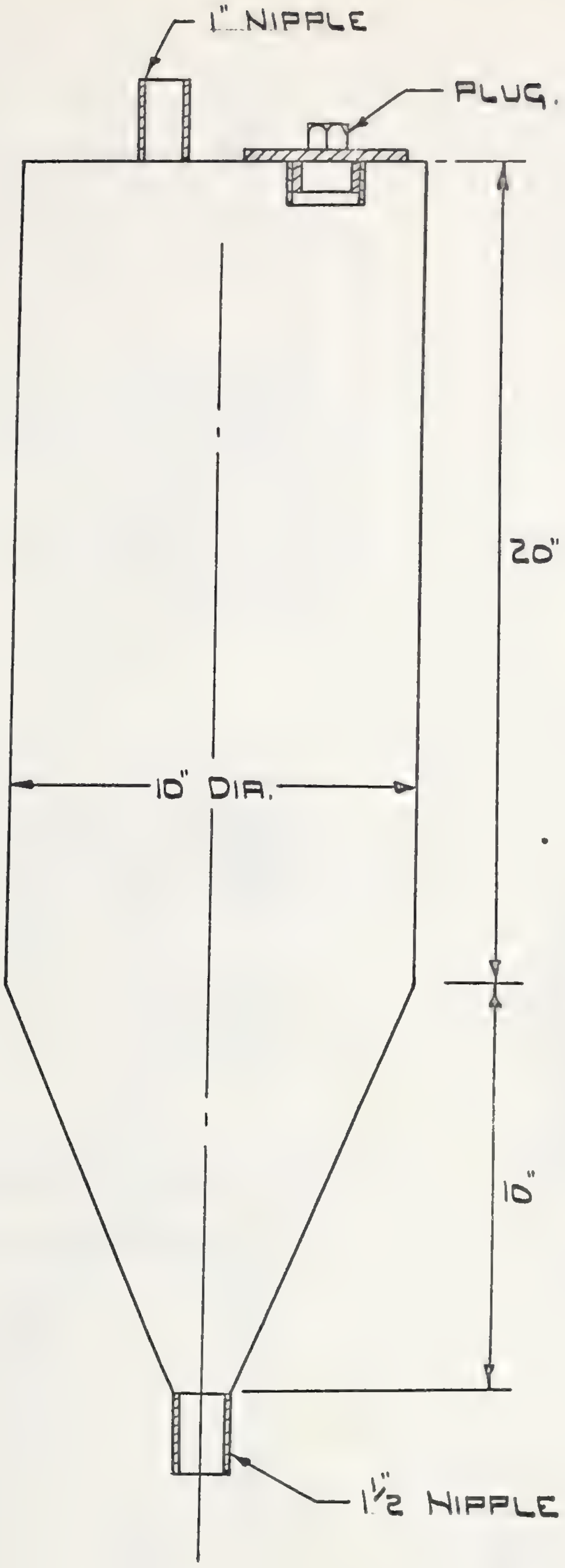
SCALE:- 2/10 FULL SIZE.

FIGURE 4.



BAG FILTER. SCALE:- 4/10 FULL SIZE.

FIGURE 5.



SOLIDS CONTAINER

FIGURE 6.

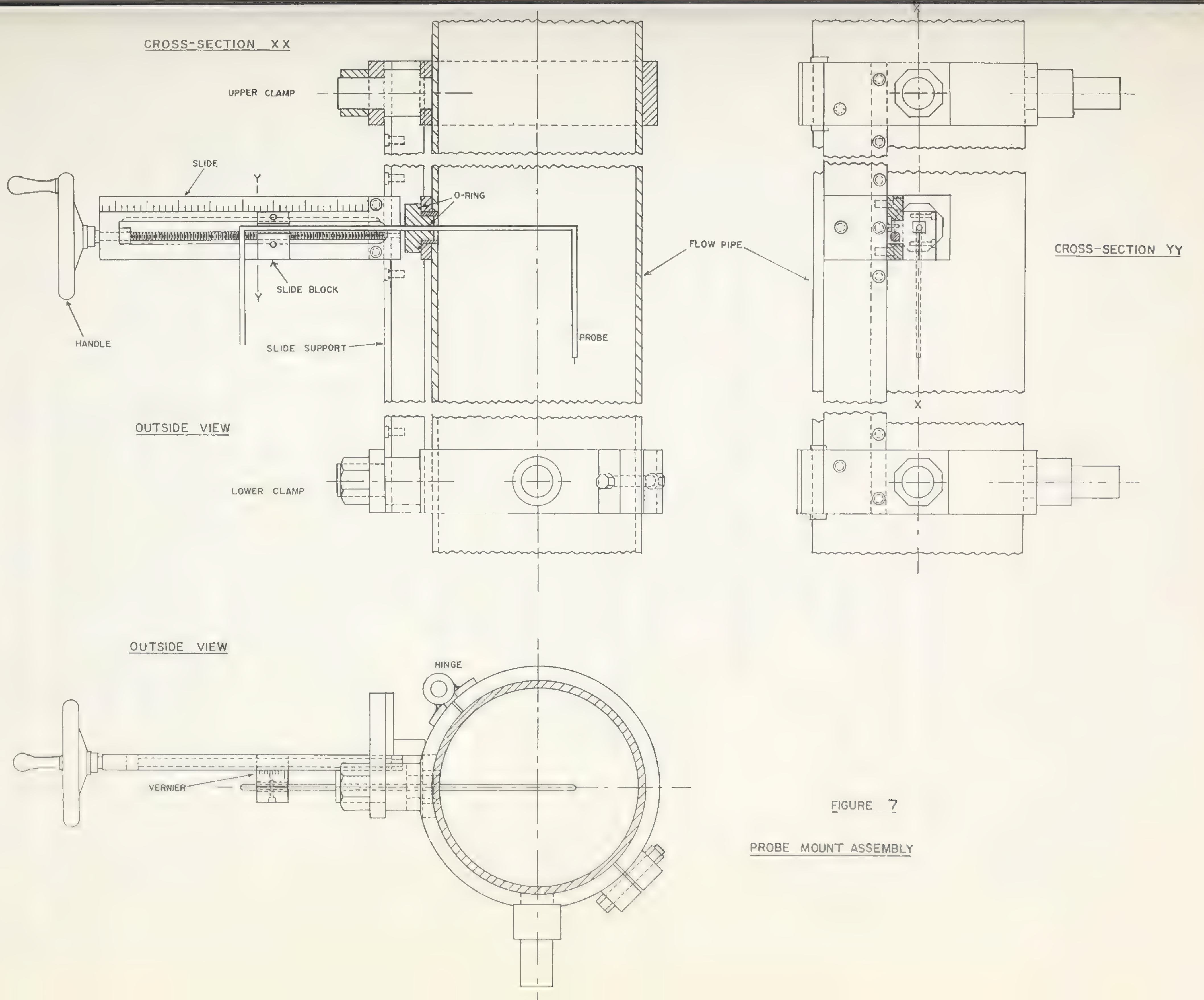


FIGURE 7

PROBE MOUNT ASSEMBLY

plane. Any of the three probes used could be clamped in the slide block by means of split sleeves which fitted around the stems of the probes. Position of the probe was read from a vernier scale carried by the slide assembly.

The support could be mounted on the pipe clamps in either of two positions. The orientation of the probe stem in one position was at an angle of 90° to the other. This arrangement allowed the measurement of two profiles at right angles to each other.

The Flow Corporation Model HWB2 Hot-Wire Anemometer.

The basic circuitry of the anemometer for mean velocity measurement is described in appendix B. Briefly the anemometer employs the constant resistance ratio (resistance ratio is the ratio of heated wire resistance to wire resistance at air recovery temperature), technique of mean velocity measurement. In this technique the current required to maintain the constant resistance ratio is a measure of the air cooling effect. The current measuring circuit included in the anemometer allows current measurement with an accuracy of $\pm \frac{1}{4}$ ma.

The resistance ratio for a given wire may be selected by means of a resistance ratio switch. Setting of resistance ratio is facilitated by use of a "hot-cold" switch. In the "cold" position only a very small current passes through the wire so that its temperature is essentially the recovery temperature of the air stream. In the "hot" position a heating current is allowed to pass through the wire. The magnitude of this current can be varied using the coarse and fine current controls so that the correct balance is obtained. In this balance position the wire resistance is equal to the resistance ratio times the resistance of the wire in the "cold" position.

Hot-Wire Probes.

A probe with a straight stem (Flow Corporation Model HWP - B) was supplied with the anemometer. A further probe designed for use in the traversing mechanism was constructed by bending a Flow Corporation Model HWP - A probe. The designs of these probes are shown in figures 8a and 8b.

Filaments on both these probes were similar and consisted of 0.00035 inches diameter tungsten wire, 0.044 inches in length in both cases. Their unheated resistance was about 3 ohms and originally they were factory mounted by copper plating and using 400° solder.

Hot-Film Probe.

The hot-film probe consisted of a platinum film mounted at the tip of a four inch long, 0.134 inches diameter wedge shaped glass rod. The unheated resistance of the film was 26 ohms. For use in the traversing mechanism the glass rod was mounted in a 0.25 inch diameter stainless steel stem as illustrated in figure 9.

The Pitot-Static Tube.

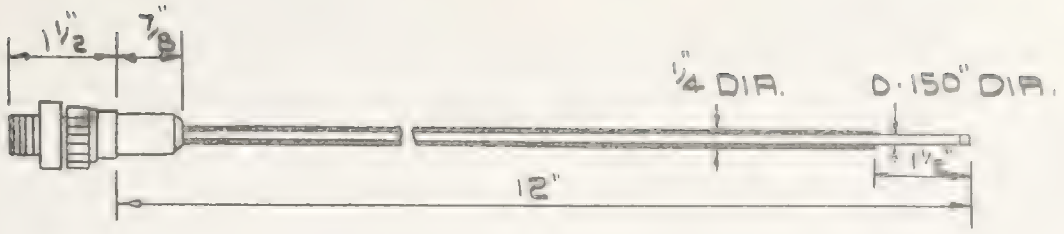
A replica of the small scale copy of the British standard used by Ower and Johansen (2) was constructed of stainless steel. The design is given in figure 10.

The Flow Corporation Model MM3 Micromanometer.

A line diagram of this instrument is given in figure 11. It consists essentially of a reservoir containing the manometer fluid and connected by flexible tubing to a slant-tube. The slant-tube can be moved in a vertical direction by means of a screw adjustment and its position read from a vernier scale. The accuracy with which vertical travel can be measured is ± 0.0002 inches. N-butyl alcohol was used as

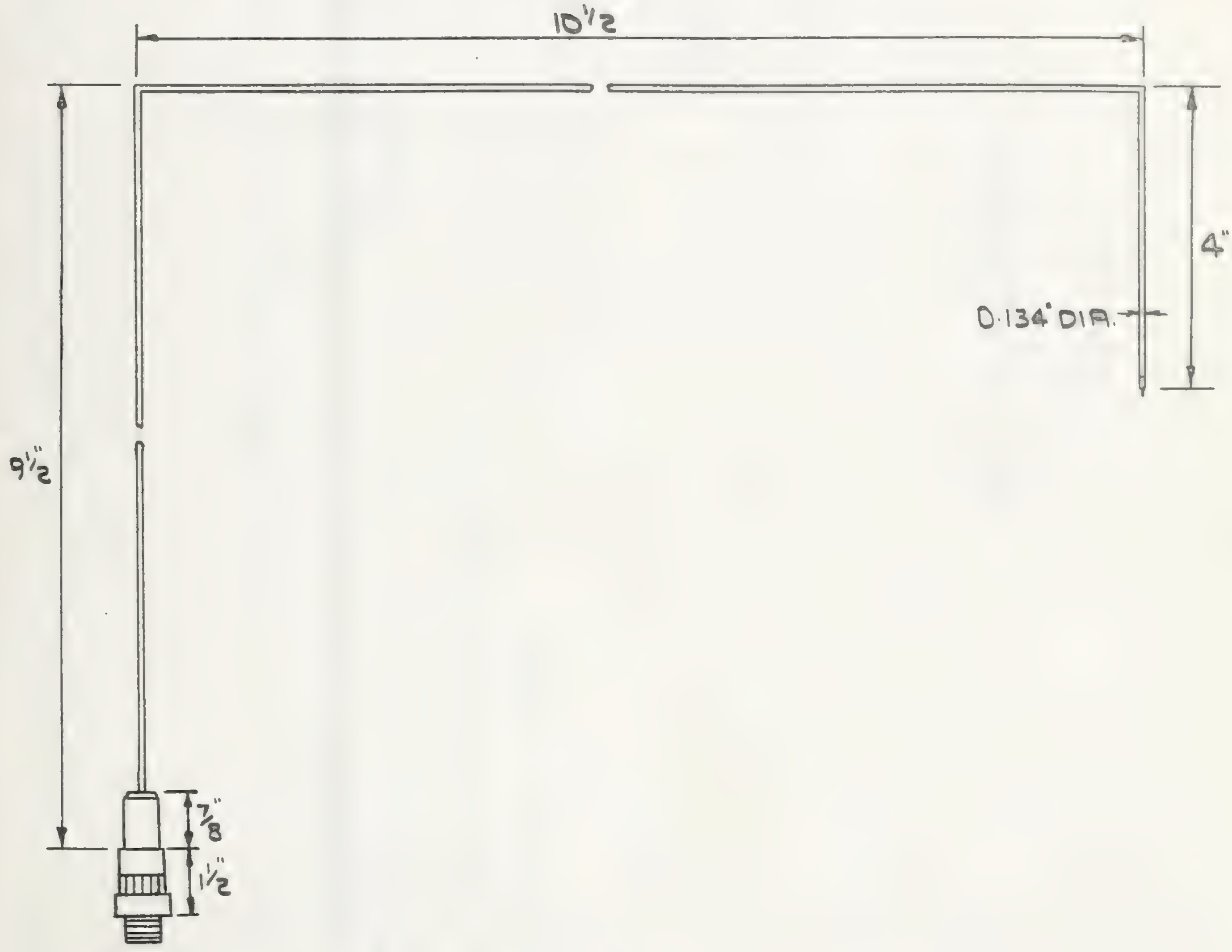
manometer fluid.

In operation the meniscus in the slant-tube is viewed through a magnifying lense and the slant-tube height adjusted in order to align the meniscus and cross-wires. When alignment is achieved the vernier scale reading is taken. One such reading is taken with the manometer outlets connected to the same pressure source (i.e. the zero reading) and one reading with outlets oonnected across the pressure differential to be measured. The difference between these readings is a measure of the pressure differential.



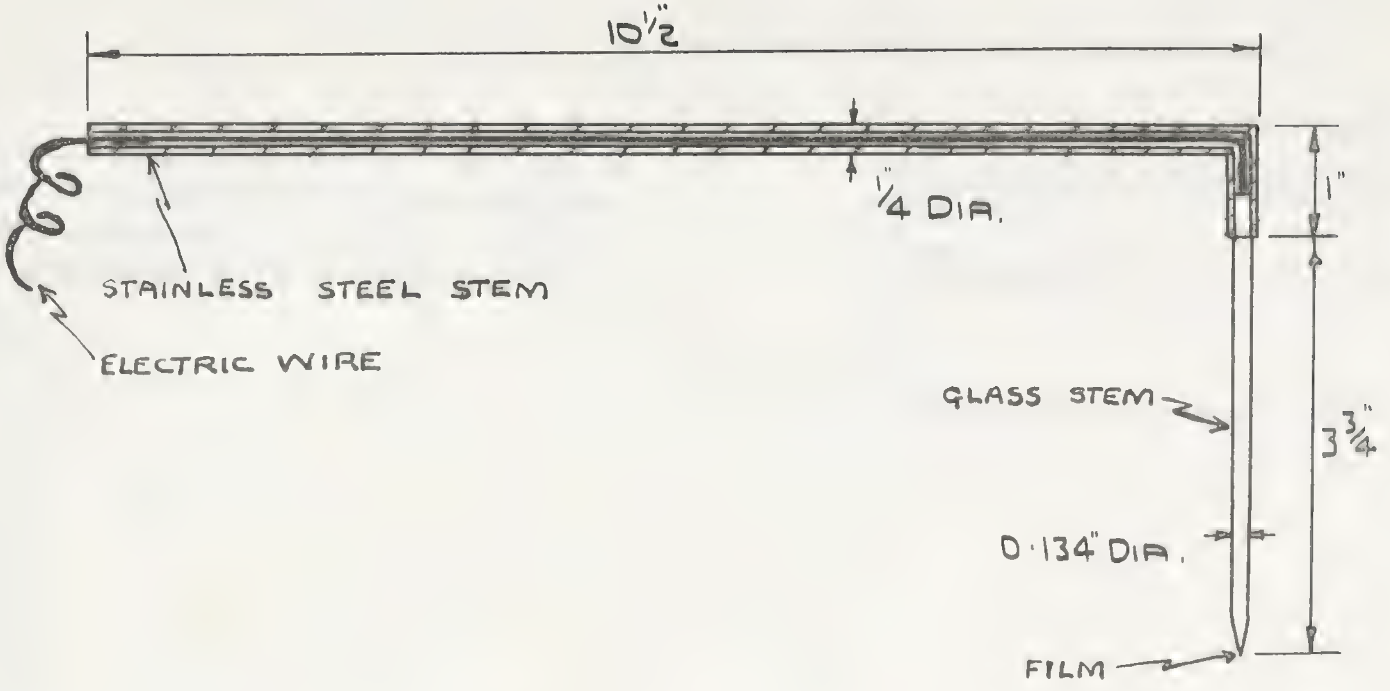
HOT WIRE PROBE - MODEL HWP-B.

FIGURE 8A.



HOT WIRE PROBE - MODEL HWP-A.

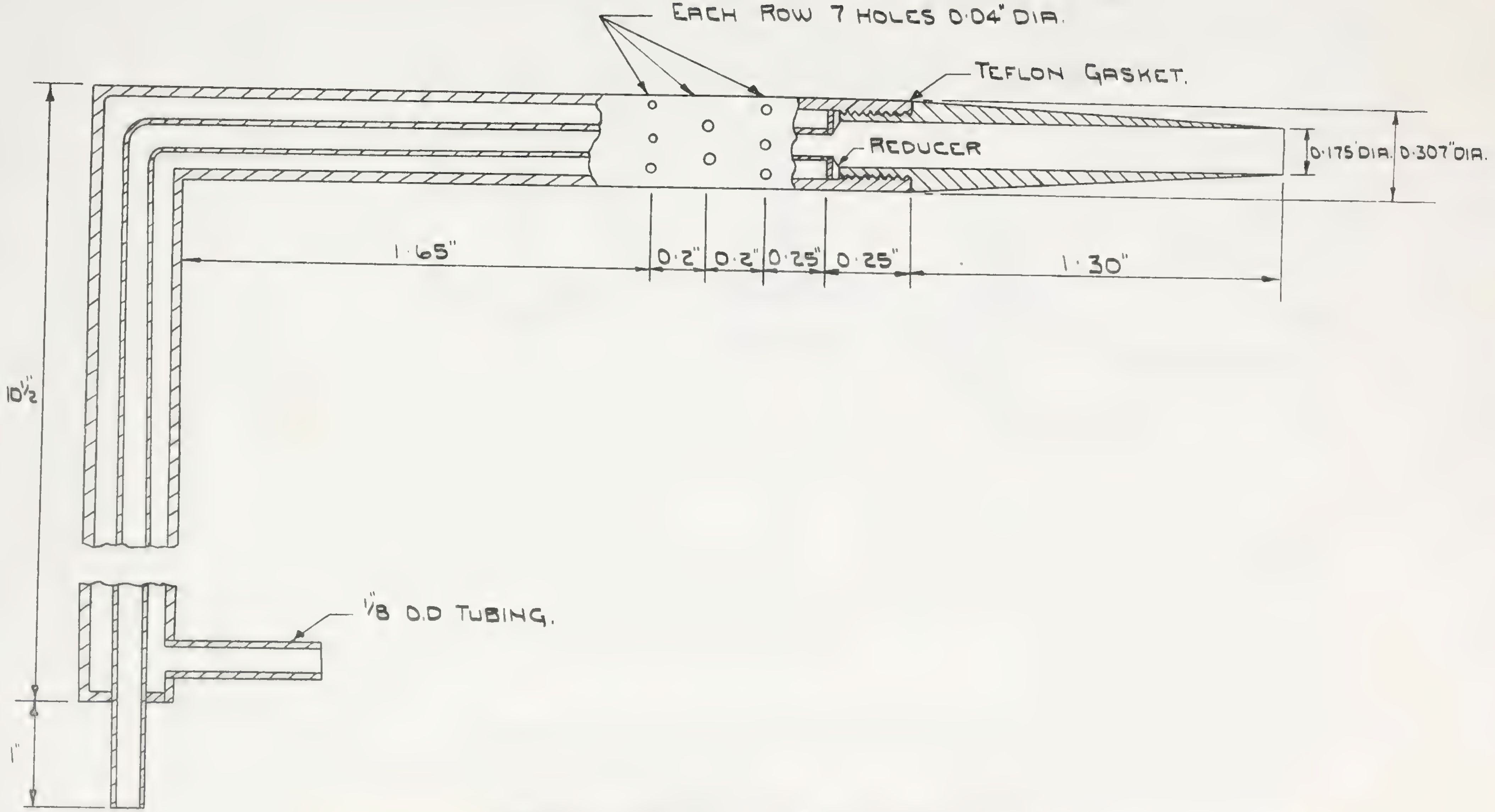
FIGURE 8B. SCALE:- ⅓ FULL SIZE.



HOT-FILM PROBE.

SCALE: ½ FULL SIZE.

FIGURE 9.



PITOT - STATIC TUBE.

SCALE:- TWICE FULL SIZE.

FIGURE 10.

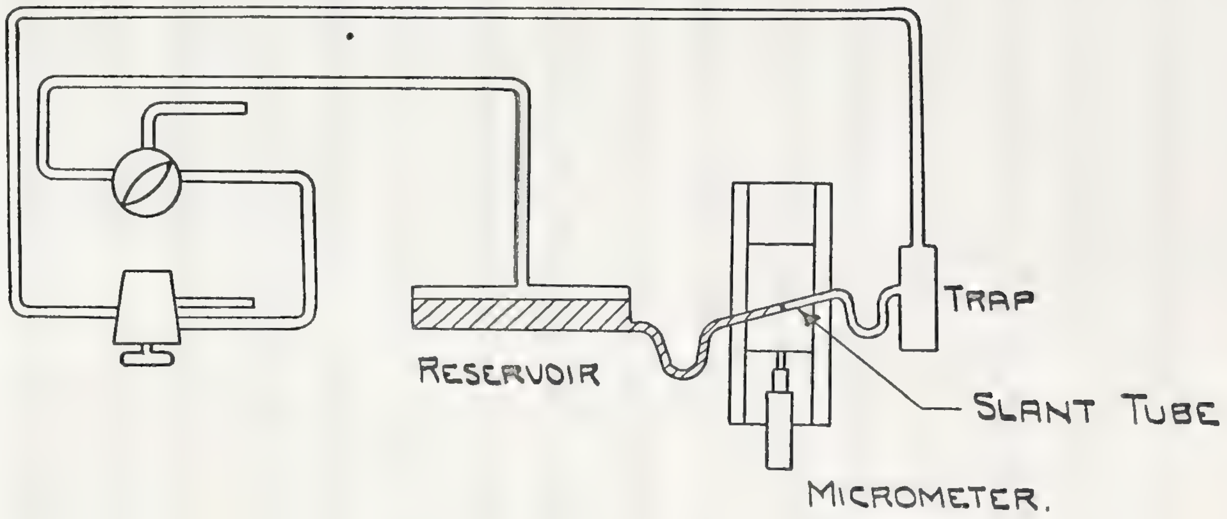


DIAGRAM OF FLOW CORPORATION

MODEL MM3 MICROMANOMETER.

FIGURE 11.

IV. OPERATION OF THE EQUIPMENT

(a) The Air System

Several experiments, designed to evaluate the operating characteristics of the air system, were performed. These tests were mainly of a qualitative nature but served the purpose of indicating the best method of operation of the equipment. The following is a summary of the results of these experiments:

1. The blower discharge had a fluctuating characteristic. The fluctuations as observed on the static pressure recorder were about 0.04 p.s.i. In addition, velocity fluctuations in the test section, observed with the pitot-static tube and hot-wire anemometer, were of such magnitude as to prevent their use for velocity measurement.
2. Increasing the back-pressure on the blower caused fluctuations in the discharge from it to increase. This increase was observed on the static pressure recorder and with the pitot-static tube. Completely opening the back-pressure valve did not reduce fluctuations sufficiently to allow velocity measurements to be made.
3. Attempts to reduce these fluctuations by including an inline capacitance downstream of the blower were unsuccessful. The increased fluctuations caused by the additional back pressure from the capacitance and necessary additional fittings were sufficient to nullify the value of the capacitance at any given flow rate. An out-of-line capacitance was also found to be of no value.
4. These experiments indicated that the only method, short of reconstruction of equipment, available for reducing the static pressure and velocity fluctuations in the test section was to discharge the air to atmosphere at the end of the test pipe. In this way, the fluctuations were reduced to a tolerable level. All velocity measurements were taken by operating

the equipment in this manner.

5. With the equipment operating in the manner described in result 4, mean air velocities in the test-pipe could be controlled over the range 5.5 - 13.0 feet per second. This range could be extended down to 0.3 feet per second by installing a 3/8 inch diameter orifice plate and removing the pressure relief valve. This flow range corresponds to a Reynolds number range of 900 - 31,000 in the test section.
6. Due to the proximity of the orifice plate to the fluctuating discharge of the blower, a particular mass flow rate could only be reproduced by reproducing the exact blower speed as well as the air weight controller setting. A calibration of the air weight controller was therefore not feasible.
7. Flowing air temperature was dependent upon the air flow rate and blower speed. A period of about 15 minutes was required for the flowing air temperature to attain a constant value.
8. Corner vanes were installed in the 90° elbow immediately preceding the entrance venturi. These were necessary to obtain symmetrical velocity profiles over the required Reynolds number range.

(b) The Flow Corporation Model HWB2 Hot-Wire Anemometer.

The anemometer was operated in the manner described in Flow Corporation Bulletin 37B (16) for mean velocity measurement. No difficulty was encountered in operation. Frequent checks of the "cold" balance were necessary at all times during the operation. These checks were rapidly made using the "hot-cold" switch as described in the suggested procedure.

(c) Hot-Wire Probes.

The maximum safe resistance ratio for use with tungsten filaments supplied by Flow Corporation was 1.4. For optimum sensitivity this resistance

ratio was used in all velocity measurements.

A wire was cleaned by immersing it in concentrated sulphuric acid saturated with potassium dichromate, as suggested in Flow Corporation Bulletin 25 (15). This resulted in a shift in the calibration curve in the direction of greater resolution in velocity measurements.

(d) The Hot-Film Probe.

On account of the high resistance (26 ohms) of the hot-film, a 15 ohm resistance was connected externally in series with pin A of the probe outlet connector. The position of this resistance in the anemometer circuitry is given in appendix B and was necessary to obtain a balance of the bridge.

Literature supplied with the hot-film probe suggested that it was usual to operate the hot film such that its heated resistance was a maximum of 1.0 ohm greater than the unheated resistance. However, to obtain such a low resistance ratio (1.04) would have required considerable modification of the anemometer circuitry. By experimentation it was found that operation of the hot-film was feasible at the lowest resistance ratio that could be obtained from the unmodified anemometer circuitry (i.e. a resistance ratio of 1.1). This resistance ratio was therefore used for all velocity measurements with the hot-film.

(e) Orientation and Location of Probes.

In all velocity measurements the orientation of the hot-wire was in a plane normal to the direction of flow and also in a plane normal to the direction of the traverse. Orientation of the wire in the plane normal to the direction of flow in the case of the model HWP-A probe, was achieved by aligning the outer leg of the probe with the axis of the test

pipe. In the case of the straight hot-wire probe (model HWP-B) it was achieved by aligning lines inscribed on the probe and slide block. These lines had been positioned so that the correct orientation was obtained on alignment.

All velocity measurements with the pitot-static tube were taken with its axis parallel to the axis of the test pipe. Correct orientation was achieved in the manner described for the model HWP-B hot-wire probe. The axis of the glass stem of the hot film probe was similarly oriented.

Probes, except the straight hot-wire probe (HWP-B), were located in relation to the wall of the pipe in the same manner. The procedure was to clamp the probes in the slide block while they were in mechanical contact with the far wall of the pipe. The reading of the vernier scale in this position could be set at a known convenient value.

The straight hot-wire probe was not used in profile measurement. The wire was located at the axis of the test pipe for calibration purposes by alignment with a probe in the 90° position.

(f) The Flow Corporation Model MM3 Micromanometer.

No difficulty was encountered in the operation of the manometer according to the instructions accompanying it. Illumination of the meniscus and cross-wire by means of a spot-light was of considerable benefit in the alignment operation. To avoid drift of the zero reading it was necessary to have the manometer set on a very rigid table. By careful operation the reproducibility in the measurement of the vertical travel of the slant tube was ± 0.0002 inches.

V. EXPERIMENTAL PROCEDURES

(a) Calibration of the Model HWP-A Hot-Wire Probe.

Calibration of the probe at an air velocity greater than approximately 4.5 feet per second was made against the pitot-static tube. At 4.5 feet per second the error in velocity measurement with the pitot-static tube is about 2 percent. In general two procedures of calibration were used. In both, the probes were oriented and positioned at the axis of the test pipe by the methods outlined in section IV (e). Air mass flow rates were controlled by setting the air weight controller and maintaining a known blower speed. No attempt was made to control the static pressure in the test section which was essentially at atmospheric pressure. Air was allowed to exhaust to the atmosphere at the end of the test pipe and time was allowed for the stabilization of flowing air temperature before any readings were taken. Data recorded during the calibration experiment are listed in table 1.

Procedure A:

i) An air mass flow rate was selected and maintained by setting the air weight controller and blower speed. Approximately 15 minutes was allowed for the stabilization of flowing air temperature. The stabilized flowing air temperature, room temperature, and barometric pressure were then recorded.

ii) The hot-wire probe was correctly positioned and oriented at the axis of the test pipe and the response of the wire recorded.

iii) The hot-wire probe was replaced by the pitot-static tube which was correctly positioned and oriented at the axis of the pipe. The response was then measured with the micromanometer and recorded.

iv) The air mass flow rate was altered by changing the air weight controller setting and, if necessary, the blower speed. Time was allowed for restabilization of flowing air temperature.

v) Steps (ii), (iii), and (iv) were repeated until the required calibration range had been covered.

iv) On completion of the calibration run the room temperature and barometric pressure were checked to ensure that no drastic changes in ambient conditions had occurred.

Procedure B:

i) The same as step (i) of procedure A.

ii) The same as step (ii) of procedure A.

iii) The air mass flow rate was altered by changing the air weight controller setting.

iv) The response of the wire at the new mass flow rate was recorded.

v) Steps (iii) and (iv) were repeated until the range of air mass flow rate which could be obtained at the particular blower speed had been covered.

vi) The hot-wire probe was then replaced by the pitot-static tube as in step (iii) of procedure A.

vii) The air mass flow rates, for which hot-wire readings had been taken, were reproduced by resetting the air weight controller as formerly. The response of the pitot-static tube at these mass flow rates was recorded.

viii) The blower speed was changed, when necessary, to extend the range of calibration and the whole procedure from step (ii) to step (vii) repeated.

ix) The same as step (vi) of procedure A.

Procedure A produces more accurate calibration points than B since reproduction of air mass flow rates using the air weight rate controller does not have to be relied upon in procedure A. A calibration using procedure B, however, was more rapidly carried out. It was found to be particularly useful when frequent calibration checks were required.

(b) Calibration of Straight Hot-Wire Probe (Model HWP-B).

At velocities greater than about 5.0 feet per second the straight hot-wire probe was calibrated against the pitot-static tube.

Except for the different method of orienting the probe as described in section IV (e), the calibration procedure was exactly the same as procedure A described in section (a) above.

Below 5 feet per second this probe was calibrated against the model HWP-A probe. Again, the procedure used was the same as A above, the pitot-static tube being replaced by the HWP-A probe.

(c) Calibration of the Hot-Film Probe.

Again, calibration of this probe at a velocity greater than about 5.0 feet per second was made against the pitot-static tube and below, against the model HWP-A probe. The procedures used were the same as A above.

(d) Measurement of Profiles with the Model HWP-A Hot-Wire Probe.

The probe was oriented in the pipe as described in section IV (e) and calibrated over the appropriate range of velocity by procedure A. After stabilization of the flowing air temperature readings of the anemometer at points along the traverse were recorded, starting from a position of contact with the far wall of the pipe. After completion of the traverse the calibration of the probe was checked to ensure that there had been no erratic change. Data recorded for each profile are listed in table 1.

Five velocity profiles were recorded to establish the calibration of the probe in the low velocity range. In these five cases a U-tube manometer was connected across the orifice and the pressure drop across it recorded at the time each profile was taken.

The orifice used was calibrated against a displacement meter which had itself been calibrated against a gas holder. These calibrations are described in appendix F.

(e) Measurement of Profiles with the Hot-Film Probe.

The procedure was the same as that described in section (d) above.

(f) Measurement of Profiles with the Pitot-Static Tube.

The pitot-static tube was oriented in the pipe as described in section IV (e) and time allowed for the flowing air temperature to stabilize. Readings of the micromanometer were then recorded at points along the traverse starting from a position of contact with the far wall of the pipe. The zero reading of the micromanometer was checked at frequent intervals during the traverse. Ambient conditions of temperature and pressure were recorded prior to and checked after each traverse. Again a list of the data recorded is given in table 1.

Table 1

Data Recorded

(a) Calibration of the HWP-A, HWP-B and Hot-Film Probes against the Pitot-Static Tube

1. Date
2. Resistance ratio
3. Room temperature
4. Barometric pressure
5. Orifice diameter
6. Blower speed
7. W.R.R.C. reading
8. Pitot-static tube pressure differential
9. Flowing air temperature
10. Hot-wire or hot-film heating current

(b) Calibration of the HWP-B and Hot-Film Probes against the HWP-A Probe

1. Date
2. Resistance ratio of HWP-B or hot-film probe
3. Resistance ratio of HWP-A probe
4. Orifice diameter
5. Blower speed
6. Room temperature
7. Barometric pressure
8. Flowing air temperature
9. HWP-B or hot-film heating current
10. HWP-A heating current

(c) Measurement of Profiles with HWP-A or Hot-Film Probes

1. Date
2. Room temperature
3. Barometric pressure
4. Flowing air temperature
5. Orifice diameter
6. Blower speed
7. W.R.R.C. reading
8. Resistance ratio of HWP-A or hot-film probe
9. Distance from pipe wall
10. Hot-wire or hot-film heating current
11. Orifice differential pressure*
12. Hot-wire heating current at zero air velocity

(d) Measurement of Profiles with the Pitot-Static Tube

1. Room temperature
2. Barometric pressure
3. Flowing air temperature
4. Orifice diameter
5. Blower speed
6. W.R.R.C. reading
7. Distance from pipe wall
8. Pitot-static tube pressure differential

* Taken in the case of five low velocity profiles only

VI. EXPERIMENTAL RESULTS

Calibration of the Hot-Wire Probe (Model HWP-A).

The results of five experimental calibrations of this probe against the pitot-static are given in tables 2C to 6C (appendix C) while the calibration curves are given in figure 12. Anemometer readings were corrected for stream temperature and the calibration curves plotted in the manner described in appendix B. The theoretical basis for the temperature correction term is also described in appendix B. The method of least squares analysis was used to determine the best fit straight line for the experimental calibration points over the range of velocities involved in each calibration series. A summary of the values of the calibration constants obtained in these analyses is given in table 14C.

Calibrations 1, 2 and 3 (Tables 2C, 3C and 4C) were taken in conjunction with hot-wire profiles 8 HW, 11 HW and 13 HW respectively. These calibrations were made for the express purpose of determining the exact calibration at the time the profile readings were recorded; they were taken prior to making the profile traverse and checked after it.

Calibrations 4 and 5 (tables 5C and 6C) were recorded as part of a general examination of the form of the calibration curve over the range 0 to 13 feet per second. They were taken at the time that profiles 1 to 5 HW (Appendix D), were recorded and frequent calibration checks during these recordings confirmed that they essentially represent the form of the calibration in the upper range of velocity (5 to 13 feet per second) for this period.

The calibration curve at a velocity of less than 1.2 feet per second was established by a trial and error procedure to obtain the best agreement between flow rates obtained by measuring the pressure drop

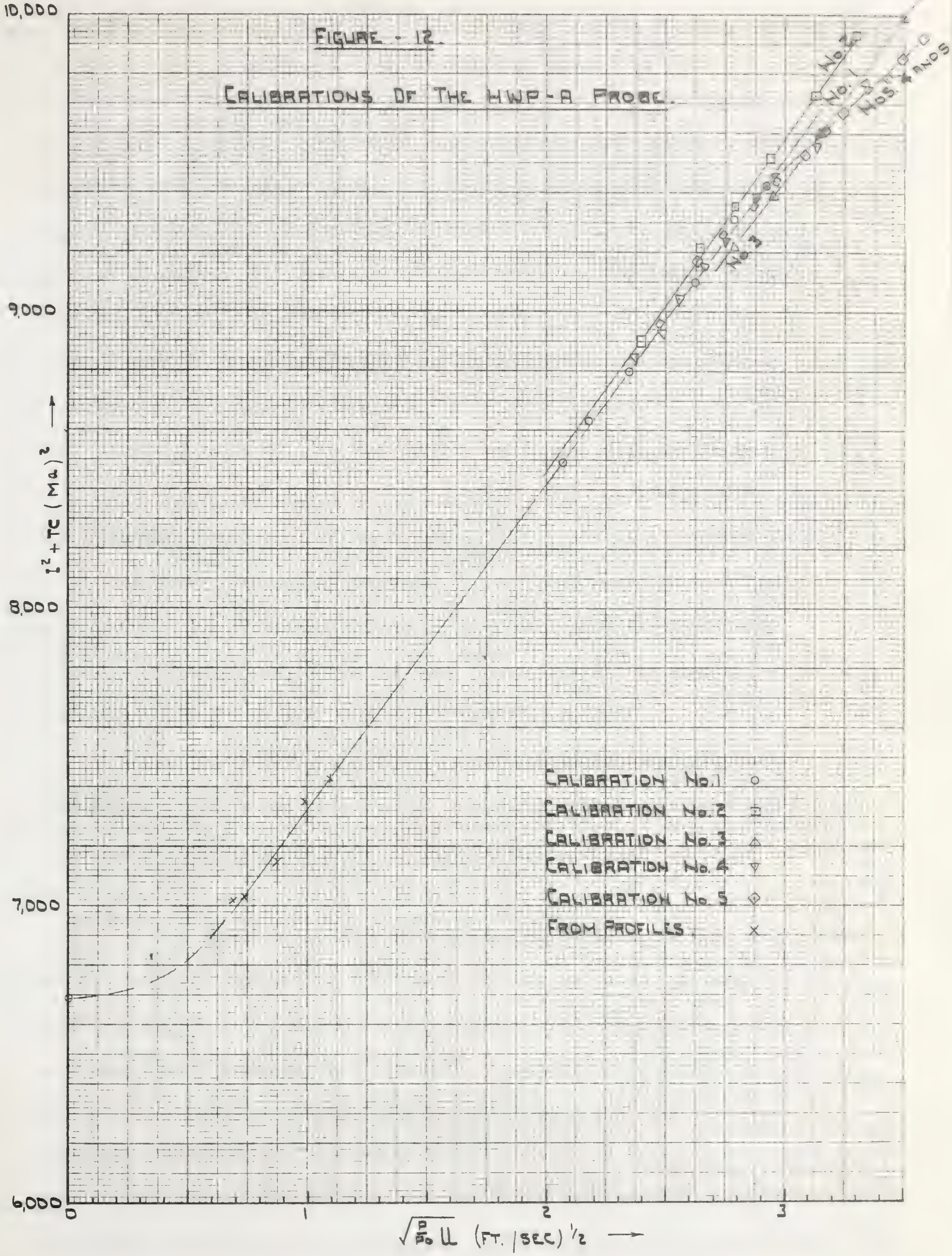


FIGURE - 12.

CALIBRATIONS OF THE HWP-A PROBE.

across the calibrated orifice and those obtained by integration of the velocity profiles. The trial and error procedure which is described in appendix E, uses the fact that an accurate value of $\frac{\bar{U}}{U_m}$ for a profile may be obtained from an approximate calibration curve by integrating the profile to obtain $\bar{U}$. A summary of the results of the trials is given in table 7C.

Five points are plotted in the range 0 to 1.2 feet per second on figure 12. These points are plots of I^2 (temperature corrected) at the centre of profiles 1 to 5 HW versus the corresponding values of $\sqrt{\frac{P}{P_o}\, U_m}$. The value of the velocity at the centre of each profile (U_m) was obtained by dividing the value of $\frac{\bar{U}}{U_m}$ for the profile into the value of $\bar{U}$ calculated from the appropriate orifice pressure drop. A least squares analysis of these five points and points from calibrations 4 and 5 was used to establish the best fit straight line for the calibration over the range of velocity 0.5 to 7.6 feet per second.

An experiment was carried out to determine the effect of resistance-ratio on the calibration. The results of this experiment are given in table 8C and plots of the calibration curves at four different resistances ratios given in figure 1C (appendix C).

The deviation of each calibration point from the best fit straight line as determined by a least squares analysis was calculated and recorded (viz. tables 2C to 6C). The maximum deviations obtained were 0.16 and + 0.23 ma. which occurred in points 27C and 39C respectively. All other calibration points had a deviation of $\pm$ 0.12 ma. or less. One division of the current measuring device on the HWB2 anemometer is equivalent to 0.25 ma. and it must therefore be concluded that the instrument can be read with an accuracy of $\pm \frac{1}{2}$ division. On this basis and assuming that

a perfectly accurate calibration curve was available, the percentage error in mean velocity measurement with the hot-wire was calculated. The results of this calculation are given in table 15C where the percentage error is compared with percentage error obtained with the pitot-static tube for the range 0 to 12 feet per second. It will be seen that the error for the hot-wire varies from 5.2 percent at 0.5 feet per second to 1.3 percent at 12 feet per second while at the same velocities the errors are 110 and 0.3 percent respectively for the pitot-static tube.

In addition to the above error, an error due to an erratic change in calibration of the hot-wire could occur if no precautions were taken with regard to calibration checks. The change which occurred between calibrations 2 and 3 indicates that this error could be of the order of 8 percent.

Calibration of the Straight Hot-Wire Probe (Model HWP-B).

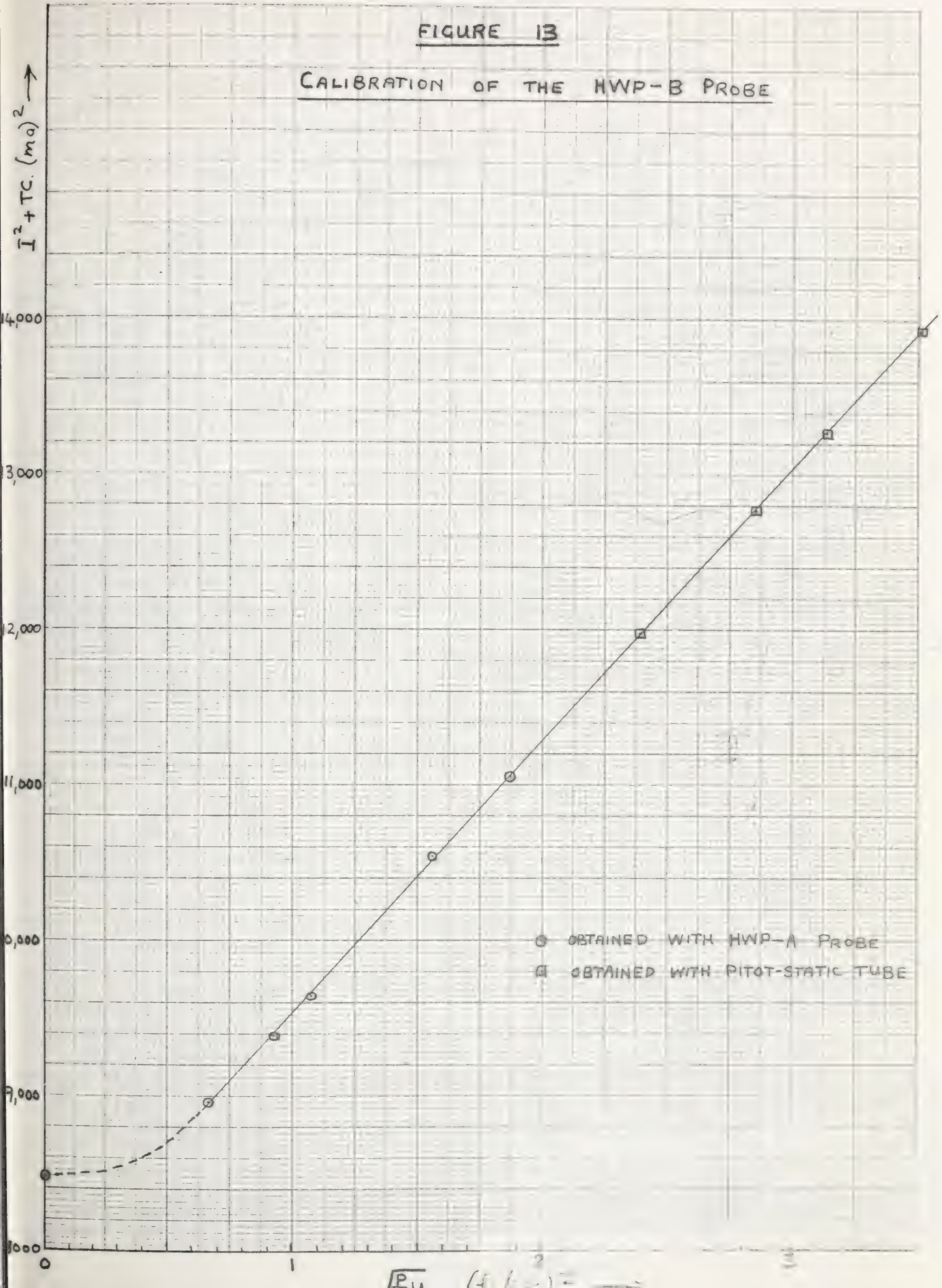
This probe was calibrated against the pitot-static tube over the range 5 to 12 feet per second and against the hot-wire probe (model HWP-A) over the range 0 to 4 feet per second. The results of these calibrations are given in tables 9C and 10C while the calibration curve obtained is shown in figure 13.

Calibration of the Hot-Film Probe.

Data of two calibrations of this probe are given in tables 11C to 13C while the curves are shown in figure 14. These curves are intended to illustrate the magnitude of change which occurred during the course of the study. The earlier calibration (no. 1) was made against the pitot-static tube over the range 4 to 11 feet per second. The later calibration (no. 2) was made against the pitot-static probe over the range 4 to 10 feet per second and against the model HWP-A hot-wire probe over the range 0.5 to 3 feet per second.

FIGURE 13

CALIBRATION OF THE HWP-B PROBE



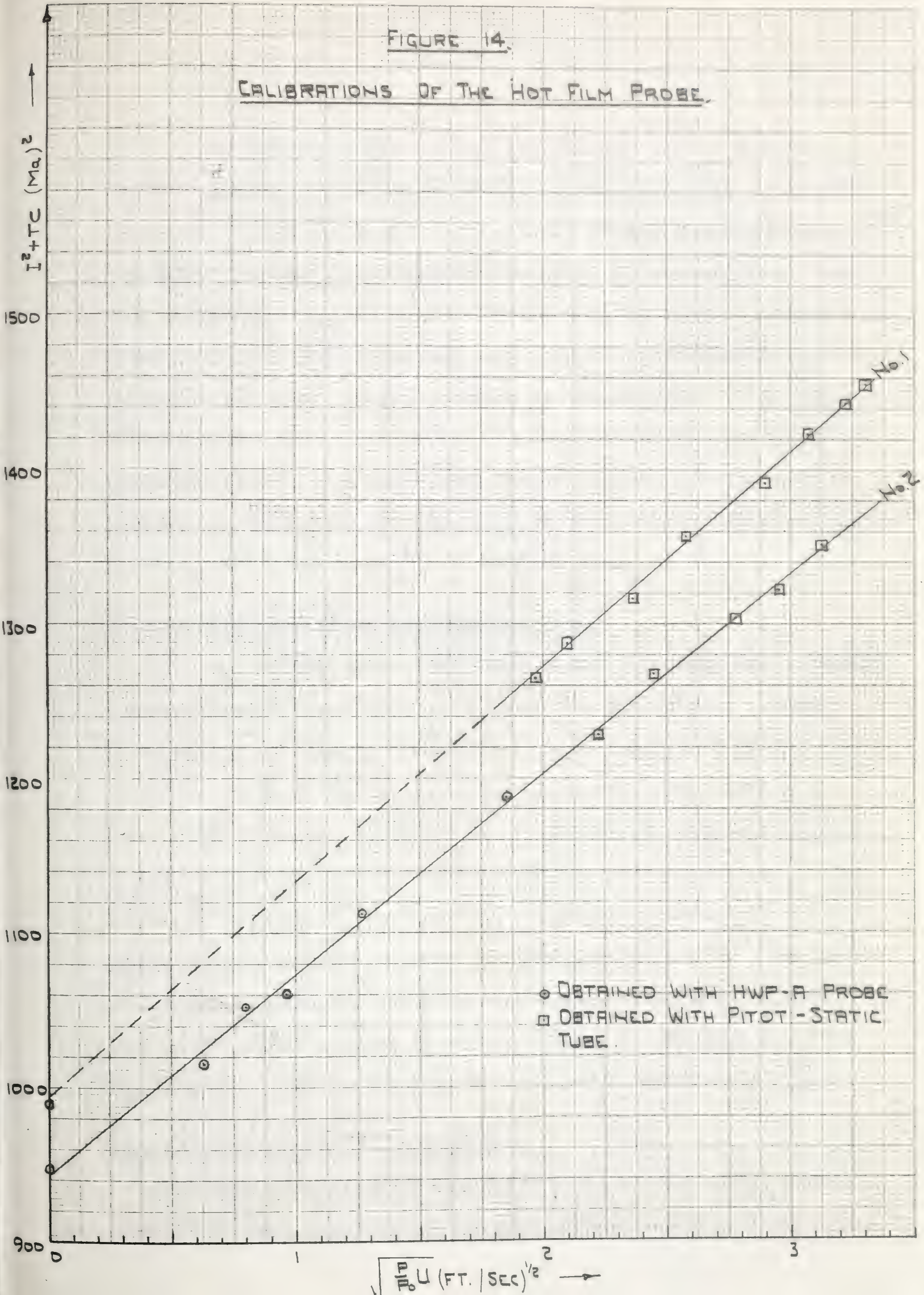


FIGURE 14.

CALIBRATIONS OF THE HOT FILM PROBE.

The deviations from the best fit straight line are given in the data tables 11C to 13C and the maximum which occurred was - 0.13 ma. in test 68C. This agrees with the conclusion reached from the hot-wire calibration that the current measuring device of HWB2 anemometer was read with an accuracy of $\pm \frac{1}{2}$ division. On this basis the error in mean velocity measurement with the hot-film probe was calculated. The results of this calculation are given in table 15C where percentage errors for the pitot-static and model HWP-A probes are also given. At 0.5 feet per second the percentage error in mean velocity measurement with the hot-film probe is 16.5 percent and at 12.0 feet per second is 4.0 percent. Additional errors may also occur due to an erratic calibration change.

Profiles measured with the HWP-A Hot-Wire Probe.

Ten profiles were recorded with the HWP-A hot-wire probe covering a Reynolds number range of 900 to 31,000 in the test section. These profiles were all taken at the main test point. Profiles 1 HW to 5 HW inclusive were taken for the purpose of calibration of the probe in the lower velocity range. Profiles 8 HW, 11 HW and 13 HW were reproductions of profiles measured with the pitot-static tube and were recorded for the purpose of comparison. The remaining two profiles, 6 HW and 7 HW, fill the gap between the five low Reynolds number profiles and the three repeats of profiles measured with the pitot-static probe. The data for these profiles are given in tables 1D to 5D inclusive, 9D, 14D and 17D (appendix D). They are illustrated in figures 15 and 16.

Profiles measured with the Hot-Film Probe.

Only one profile was measured with the hot-film probe, profile 8 HF. This was a reproduction of a profile measured with both the pitot-

static and hot-wire probes and was recorded for the purpose of comparison. Data for the profile are given in table 10D and it is illustrated in figure 16.

Profiles measured with the Pitot-Static Probe.

The pitot-static probe, being the most sensitive instrument available for measurement above a velocity of about 5 feet per second, was used for the investigation of profiles in the range 5 to 13 feet per second. Six profiles were taken at the main test point covering the range of Reynolds number 17,000 to 31,000. Data for the profiles are given in tables 8D, 11D, 12D, 13D, 15D and 16D. They are plotted in figure 16.

FIGURE 15 - PLOTS OF PROFILES 1 TO 7.

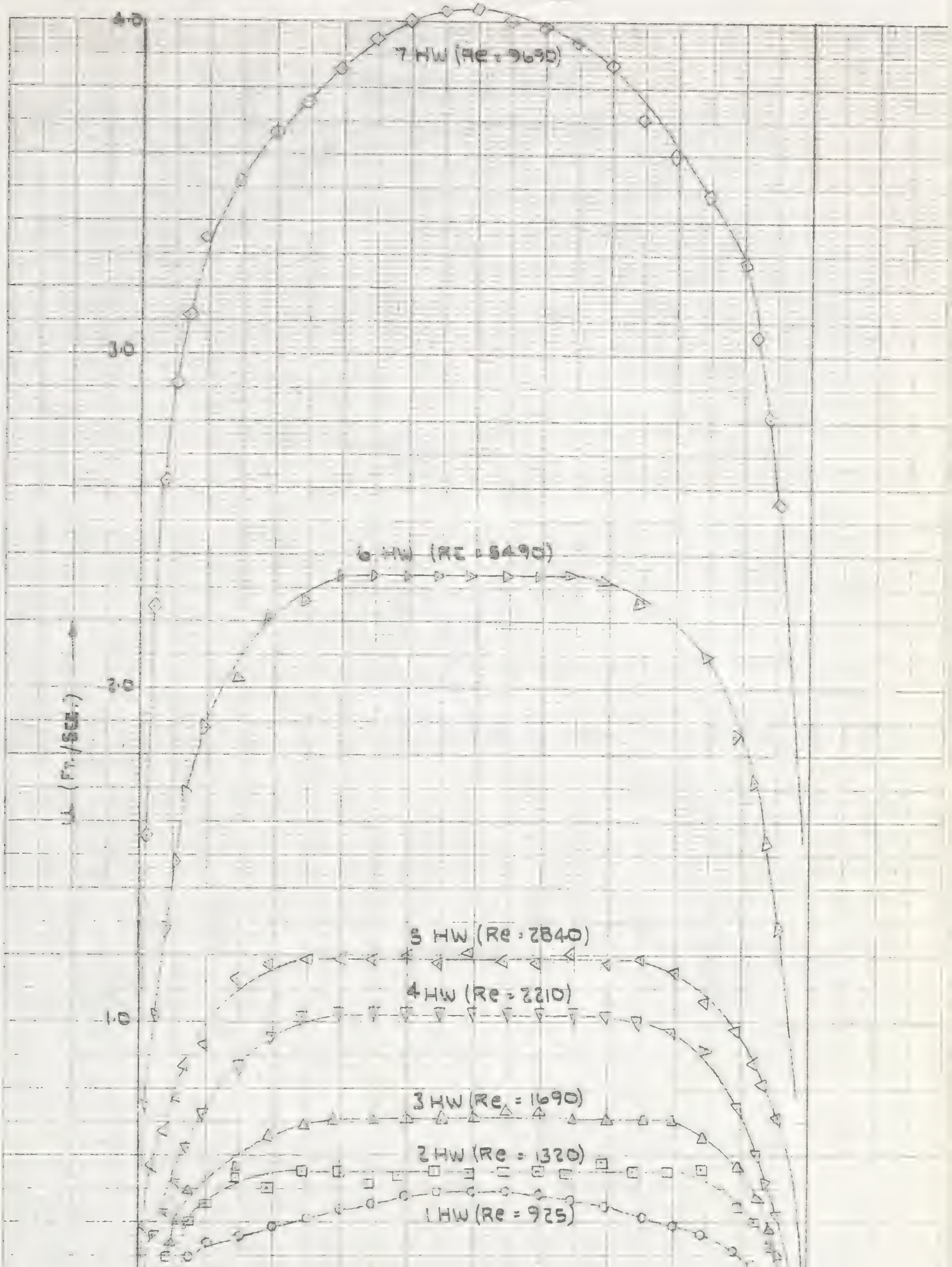
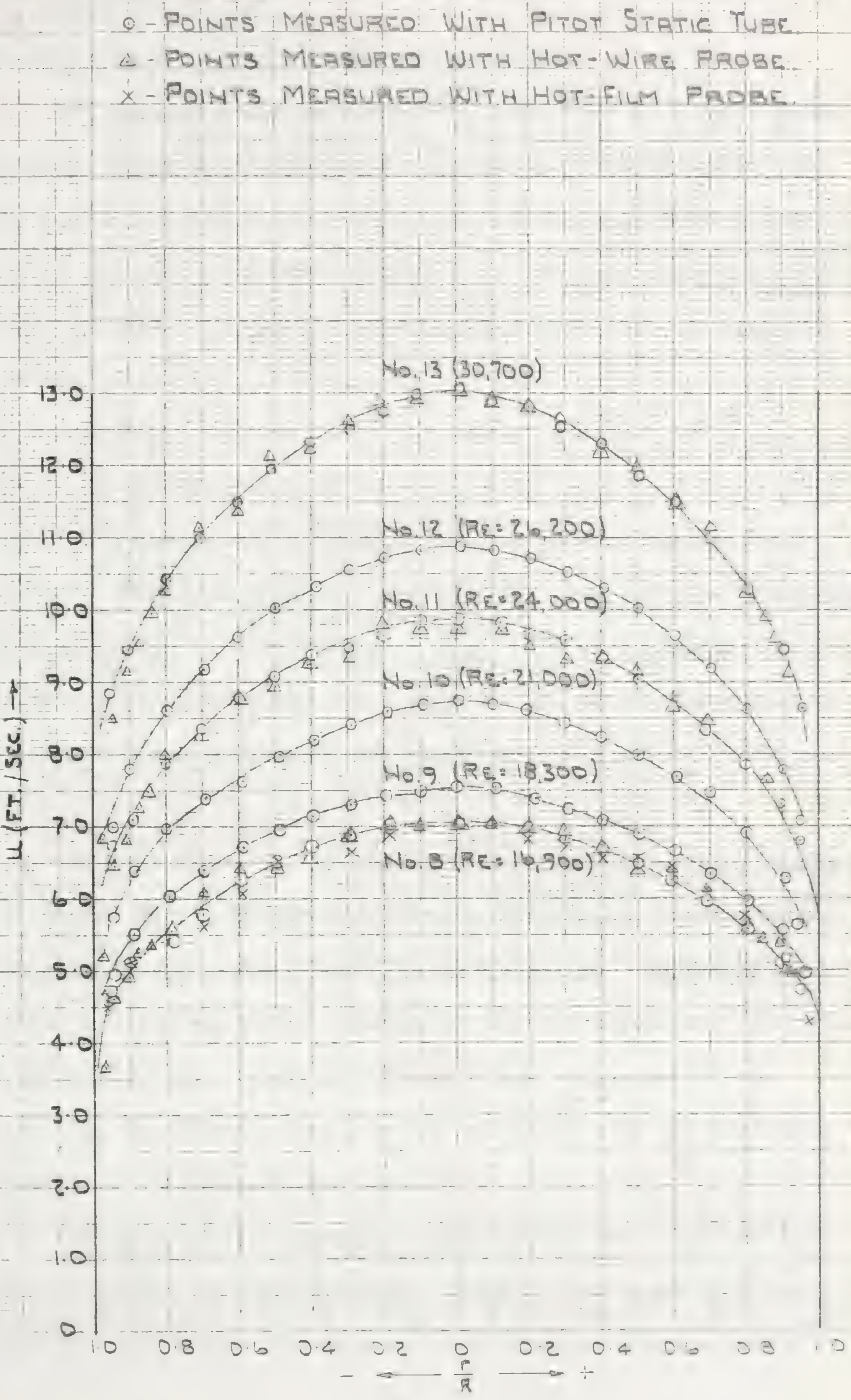


FIGURE 16.

PLOTS OF PROFILES 8 TO 13.



VII. DISCUSSION OF RESULTS

Calibration of the Hot-Wire Probe (Model HWP-A)

The least squares analyses of calibrations 1, 2 and 3 prove that straight lines can be drawn through the calibration points such that the maximum deviation occuring is within the experimental error expected in the use of the HWB2 anemometer. It must therefore be concluded that these calibration curves are linear over the measured ranges of velocity.

Calibration curves 4 and 5, however, are not linear. Sensitivity of the wire in both cases decreases with increasing air velocity. The reason for this would seem to be that calibrations 1, 2 and 3 were made early in the life of the wire, while calibrations 4 and 5 were made after considerable usage. As is suggested in literature (15, 16), fine room dust from the air stream had probably accumulated on the wire causing the non-linear calibration in cases 4 and 5.

The operation of cleaning wires using concentrated sulphuric acid, saturated with potassium dichromate, causes considerable shift in calibration as was demonstrated in early trials. No attempt was made to correct the curvature observed in calibrations 4 and 5 because further investigational work was planned which would rely on the calibration in the lower velocity range established by the measurement and integration of velocity profiles.

The five calibration points, obtained by the trial and error procedure to obtain the best agreement between flow rates measured by means of the orifice and flow rates obtained by the integration of

velocity profiles taken with the HWP-A probe, confirm the linearity of the calibration down to a velocity of 0.5 feet per second. The diameter of the wire on the HWP-A hot-wire probe was 0.00035 inches. Using these values the critical value of Ud which characterizes the lower limit of linearity is 1.46×10^{-5} feet^2 per second and the corresponding value of Reynolds, based upon wire diameter, is 0.082. The former compares favourably with the critical value of $Ud = 2.01 \times 10^{-5}$ feet^2 per second deduced theoretically by King (8), while the latter is in fairly good agreement with the value of Reynolds number, $Re = 0.108$, quoted by Weske (14).

Although no consistent deviation from linearity was observed above 0.5 feet per second, it is evident that the linearity of calibration cannot be accepted without question in the lower velocity range. It should also be realized that the deviation from linearity is not connected with the transition from a turbulent to laminar boundary layer around the wire. Calculation shows that this transition would not occur for the wire on the HWP-A probe until an air velocity of 6.0×10^5 feet per second was attained.

The deviations of practically all of the calibration points as determined by least squares analysis are less than ± 0.13 ma. This is well within the limits of accuracy of current measurement with the HWB2 anemometer as given in Flow Corporation literature (15, 16) wherein it is stated that current measurement can be made with an accuracy of $\pm \frac{1}{4}$ ma.

The estimated percentage error in mean velocity measurement with HWP-A probe is given in table 15C (appendix C). The error varies from ± 1.3 percent at 12 feet per second to ± 5.2 percent at 0.5 feet per second. The error quoted in Flow Corporation literature is ± 2 percent when a calibration curve based on several experimental points is available.

Sleicher (18) in a comparable study obtained accuracies of ± 0.5 percent at moderate velocities decreasing to ± 5 percent at 7 feet per second, while Dryden and Kuethe (13) found it difficult to secure an accuracy of better than ± 1.5 percent. It can be concluded therefore that the HWB2 hot-wire anemometer is capable of measuring mean velocity with an accuracy comparable to that obtained with hot-wire anemometers described in the literature.

The deviations from the best-fit straight line of the five calibration points in the very low velocity range, obtained by the trial and error procedure, are given in table 7C where they are expressed as percentage deviation in velocity. The maximum deviation which occurs is + 6.4 percent in the profile with the lowest centre line velocity (0.47 feet per second). According to table 15C the estimated error in mean velocity measurement for the HWP-A probe is 5.2 percent at a velocity of 0.5 feet per second. The close agreement between this value and that observed experimentally verifies the validity of the errors given in table 15C for the HWP-A probe.

The pitot-static tube, as can be seen from table 15C is a more accurate instrument for the measurement of mean velocity than the HWB2 anemometer in flows having a velocity greater than 5 feet per second. The anemometer has the further disadvantage that an erratic change of calibration could result in an error in mean air velocity of the order of 8 percent.

Calibration of the Straight Hot-Wire Probe (Model HWP-B).

The calibration curve for this probe as seen in figure 13 is linear over the range 0.5 to 12.0 feet per second. The lower limit of the linearity occurs at a value of $Ud = 1.46 \times 10^{-5}$ feet^2 per second which

is the same as that obtained in the case of the HWP-A probe. It must therefore be concluded that termination of linearity in the lower velocity range is not dependent upon the orientation of the probe stem in relation to the air flow direction.

Calibration of the Hot-Film Probe.

The calibration curves for this probe are illustrated in figure 14 while the deviations from the best fit straight lines are given in tables 11C, 12C and 13C. The results obtained indicate that the calibration curves, plotted in the same manner as for wires, are linear. Linearity extends over the whole range from 0 to 11 feet per second. However, it should be realized that this is based on the assumption that no air temperature correction is required. The application of the air temperature correction used for wires was felt to be unjustified because this correction is suggested for use with Flow Corporation probes only (15, 16) (see appendix B).

The estimated error in the measurement of mean velocity with the hot-film probe is given in table 15C. The error varies from 4.0 percent at 12 feet per second to ± 16.5 percent at 0.5 feet per second. The error at any velocity is approximately three times the error obtained using a hot-wire probe. In addition a change of 30 percent occurred in the calibration during the course of the experiments. Such a change could cause further errors in velocity measurement with the hot-film probe if sufficient precautions were not taken with regard to calibration checks.

Profiles Measured with the HWP-A Hot-Wire Probe.

The profiles measured with the HWP-A probe cover the complete range of Reynolds number (i.e. 900 - 31,000) studied. However, only

profiles in the Reynolds number range 17,000 to 31,000 are fully developed. The justification for this statement is illustrated in figures 17 and 18 where it can be seen that profile 7 HW for a Reynolds number of 9,700 does not conform with a fully developed profile. Profiles for Reynolds numbers less than 9,700 are not plotted in figures 17 and 18 to avoid confusion. If plotted they would display an increasing nonconformity with a fully developed turbulent profile as Reynolds number decreased. Partially developed profiles, except profile 1HW, are flatter in the centre and less steep near the wall than a fully developed turbulent profile. Profile 1HW, which is for a Reynolds number of 925, appeared to be a partially developed laminar profile.

The three fully developed profiles (Nos. 8HW, 11HW, 13HW), measured with the HWP-A probe, are reproductions of profiles measured with the pitot-static tube. As seen in figure 16, there is good agreement between profiles measured with these probes although there is slightly more scatter in points taken with the hot-wire.

Profiles measured with the Hot-Film Probe.

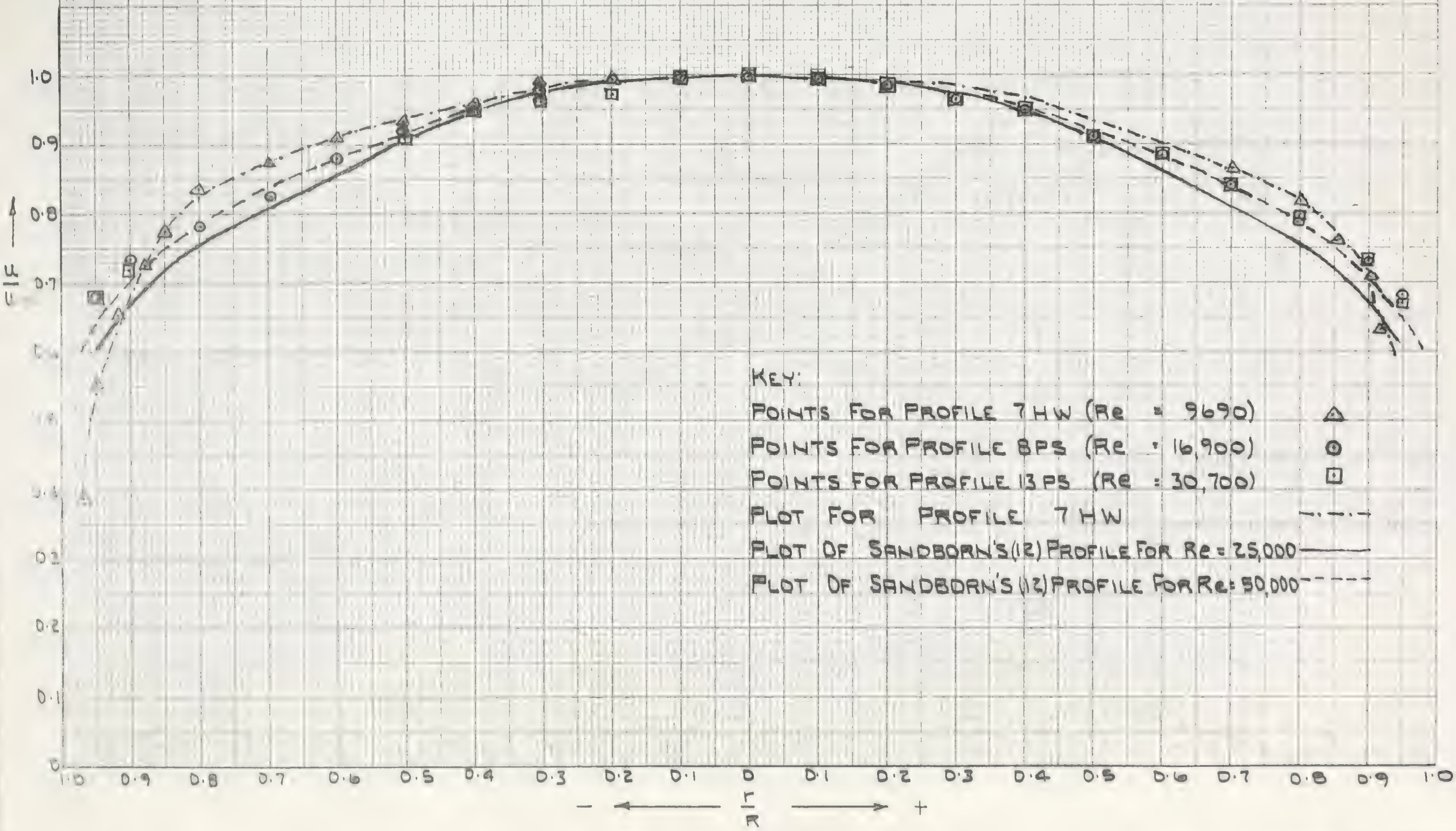
The only profile measured with the hot film probe is a reproduction of profile 8PS measured with the pitot-static tube. The agreement, as can be observed in figure 16, is good although considerably more scatter occurs in the points taken with the hot-film probe.

Profiles measured with the Pitot-Static Tube.

The six profiles measured with the pitot-static tube cover the range of Reynolds number 17,000 to 31,000 and are all fully developed.

FIGURE 17.

PLOT OF DIMENSIONLESS VELOCITY $\frac{u}{u_b}$ VERSUS DIMENSIONLESS RADIUS $\frac{r}{R}$ FOR PROFILES.



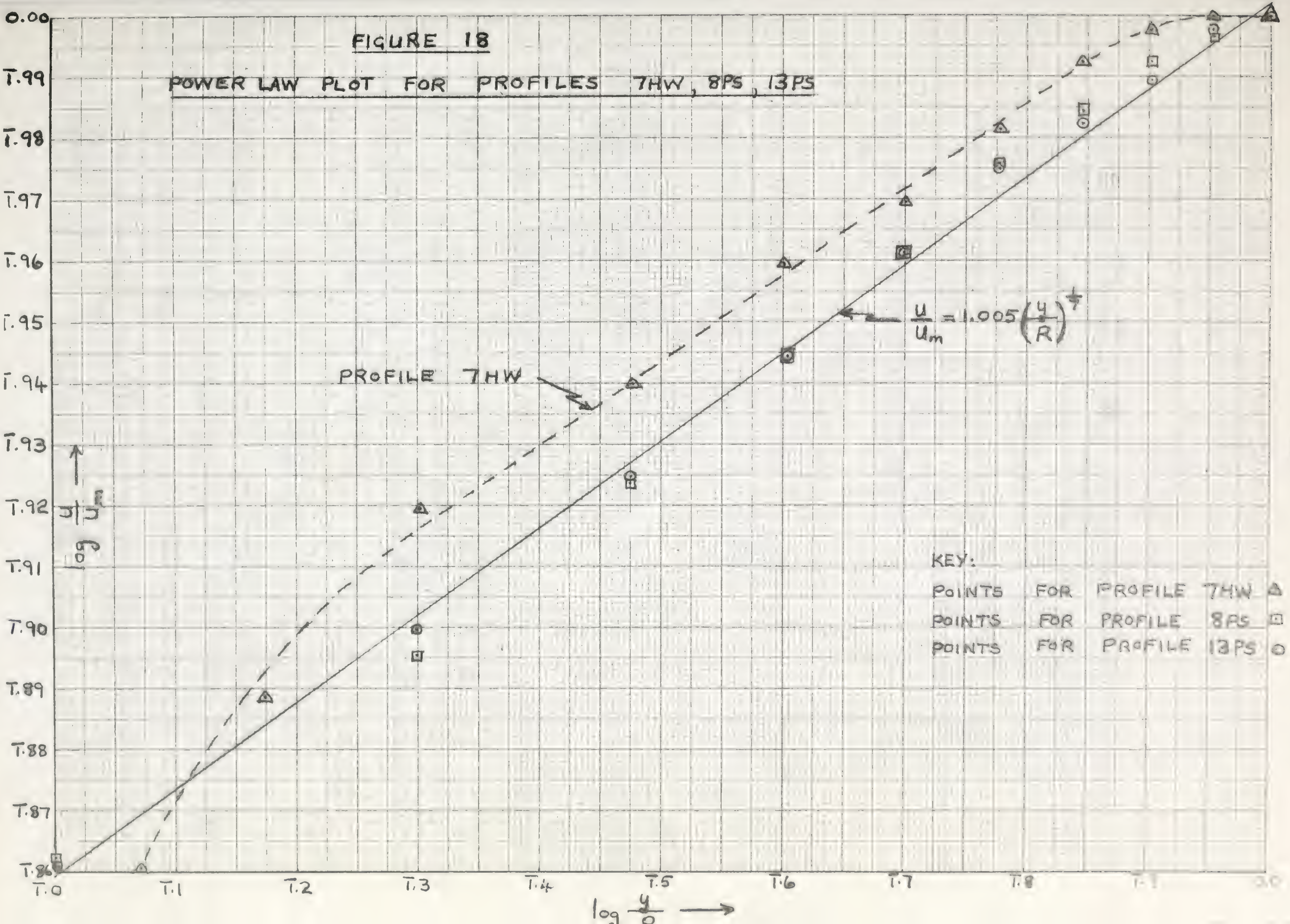


FIGURE 18

POWER LAW PLOT FOR PROFILES 7HW, 8PS, 13PS

Plots of dimensionless velocity $\frac{U}{U_m}$ against dimensionless radius $\frac{r}{R}$ for these profiles are shown in figure 17 along with some profiles obtained by Sandborn (12) which have been included for comparison. As will be observed the profiles agree with those of Sandborn.

A plot of log $\frac{U}{U_m}$ against log $\frac{r}{R}$ is given in figure 18, illustrating the conformity of the data to the power law:

$$\frac{U}{U_m} = 1.005 \left(\frac{y}{R}\right)^{1/7} \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} (7a)$$

which is in agreement with that given in literature (4, 30) for Reynolds numbers up to about Re = 10^5. Using the Blasius friction factor equation:

$$f = 0.0791 \, (Re)^{-\frac{1}{4}} \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} (9)$$

equation (7) can be put in the form:

$$\frac{U}{U_*} = 8.57 \left(\frac{yU_*\rho}{\mu}\right)^{1/7} \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_} (10)$$

The corresponding constants for this equation, given in reference 31, are 8.56 and 1/7.

Figure 19 illustrates the conformity of the data with the universal velocity distribution equation. The data agree more closely with the equation suggested by Deissler (24):

$$\frac{U}{U_*} = 3.8 + 2.78 \ln \left(\frac{y\,U_*\rho}{\mu}\right) \text{\_\_\_\_\_\_\_\_\_\_\_\_} (11)$$

than that suggested by Nikuradse as reported by Knudsen and Katz (4). Some divergence from the line represented by equation 11 occurs in points taken near the pipe wall. This is possibly due to the relatively large diameter opening of the pitot-static tube which would manifest itself in points taken near the wall.

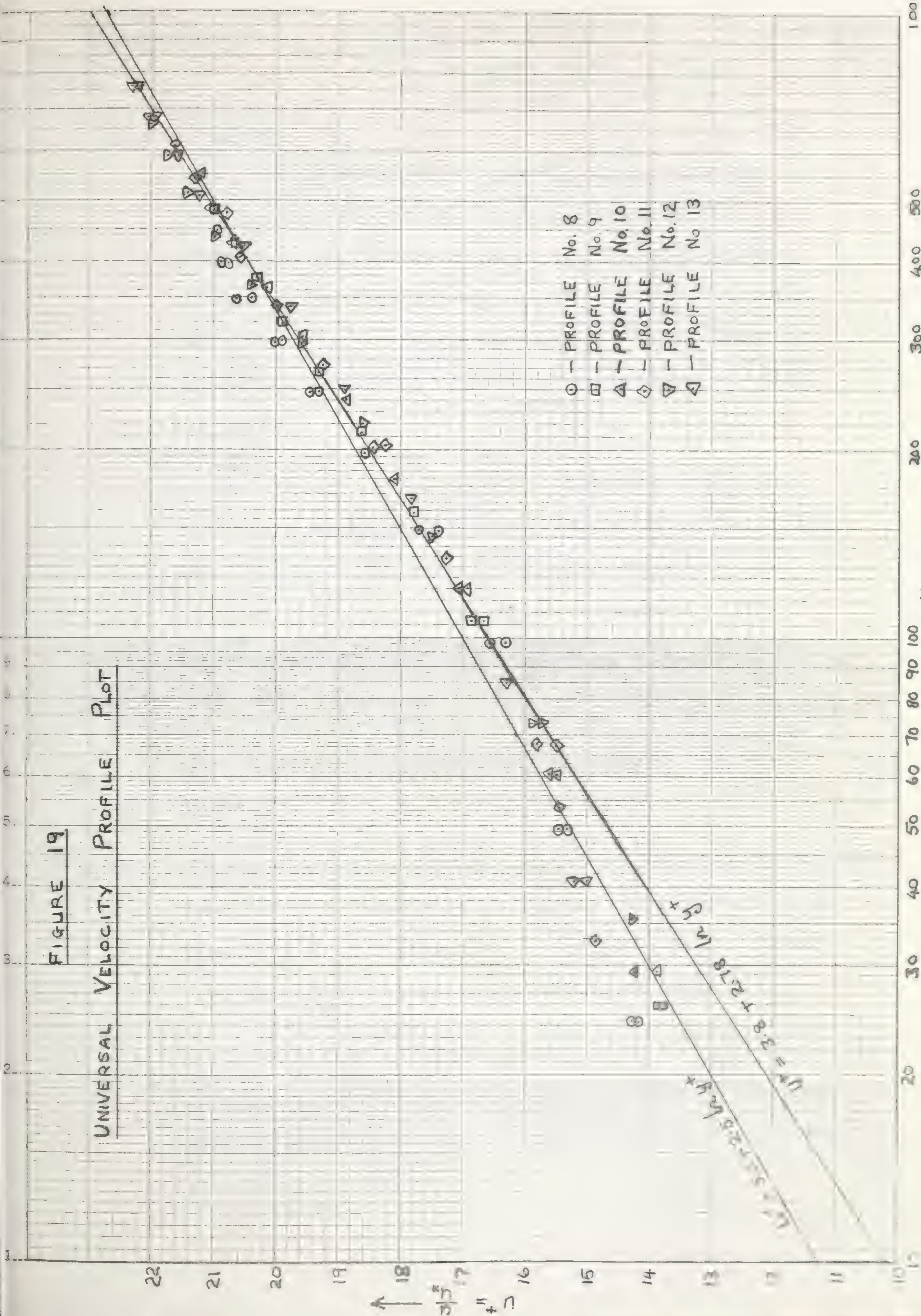


FIGURE 19
UNIVERSAL VELOCITY PROFILE PLOT

VIII. CONCLUSIONS

1. King's formula, modified as suggested in Flow Corporation literature (15, 16) for use with the constant resistance ratio circuitry of the HWB2 anemometer, correctly describes the calibration curves of the wires investigated over the range of air velocity 0.5 to 13.0 feet per second. Within this range calibration curves can be plotted in such a manner that they are linear.

2. At approximately 0.5 feet per second departure from the linear form of calibration curve occurs. Calibration curves for the Model HWB2 hot-wire anemometer using HWP probes cannot be extrapolated to zero air velocity as is suggested in Flow Corporation literature (15, 16).

3. The form of the calibration curve for the hot-wire is independent of orientation of the probe stem with respect to the air flow direction.

4. The error in mean velocity measurement using the hot-wire equipment described in this thesis is ± 1.3 percent at 12 feet per second increasing to ± 5.2 percent at 0.5 feet per second. Further error may result from an erratic calibration change.

5. The error in mean velocity measurement using the pitot-static tube in combination with the micromanometer described in this thesis, is ± 0.3 percent at 12 feet per second increasing to ± 2.5 percent at 4.0 feet per second.

6. The error in mean velocity measurement using the hot-film probe in combination with HWB2 anemometer is ± 4.0 percent at 12 feet per second increasing to 16.5 percent at 0.5 feet per second. Further error may result from an erratic calibration change.

7. The pitot-static tube is a better instrument than the hot-wire for the measurement of mean velocities greater than about 5 feet per second. The hot-wire is superior to the hot-film in low velocity flows containing no suspended solid.

8. Frequent calibration checks are required in the operation of hot-wire and hot-film probes in order to minimize errors due to erratic changes.

9. The equipment described in this thesis permits the study of profiles over the range of Reynolds number 900 to 31,000, with an accuracy comparable to that of other investigators.

10. Profiles in the Reynolds number range 17,000 to 31,000 were fully developed. The data for these profiles agree closely with the universal velocity distribution equation suggested by Deissler (24).

NOMENCLATURE

A, B, C, C_1, C_2, C_3	constants, to be evaluated empirically
d	wire diameter
f	Blasius friction factor
f_1	function of wire dimensions and $(T_w - T)$
f_2	function of wire dimensions and $(T_w - T)$
g_c	gravitational constant
H	heat loss per unit length of wire
I	heating current to wire
I_o	heating current at zero air velocity
$\overline{I}$	heating current requirement according to calibration
K	pitot-static tube factor
k_1, k_2	constants, to be evaluated empirically
P	absolute pressure
P_o	reference pressure (70 cm. Hg.)
ΔP	dynamic or impact pressure
R	pipe radius
R_e	Reynolds number
r	radius
T	air temperature
T_w	hot-wire temperature
t_w	shear stress at the pipe wall
U	mean flow velocity at measuring point
U_{corr}	velocity correction
U_m	velocity at pipe axis
U_w	velocity to which the wire responds

$\overline{U}$	average velocity of flow in pipe
U_*	friction velocity = $\sqrt{\frac{t_w g_c}{\rho}}$
u	velocity fluctuation component in the direction of U
v	velocity fluctuation component in the direction of traverse
w	velocity fluctuation component in the plane of traverse and normal to the direction of the traverse
y	R - r
μ	coefficient of viscosity of air
ρ	density of air

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APPENDICES

APPENDIX A

THE PITOT-STATIC TUBE

THE PITOT-STATIC TUBE

The equation expressing the relationship between the dynamic or impact pressure ΔP which is measured with the pitot-static tube and the velocity of the fluid is:

$$U = \sqrt{\frac{2Kg_c \Delta P}{\rho}} \qquad (1)$$

The value of the calibration constant K for a given instrument must be determined by calibration.

In the work described in this thesis a small scale copy of the British standard pitot-static tube was used. This instrument was calibrated in 1931 by Ower and Johansen (2) over the range of air velocity 1.75 to 27.03 feet per second. The value of the calibration constant K at various air speeds, obtained in this study, is given in table 1A. A plot of the data is shown in figure 1A.

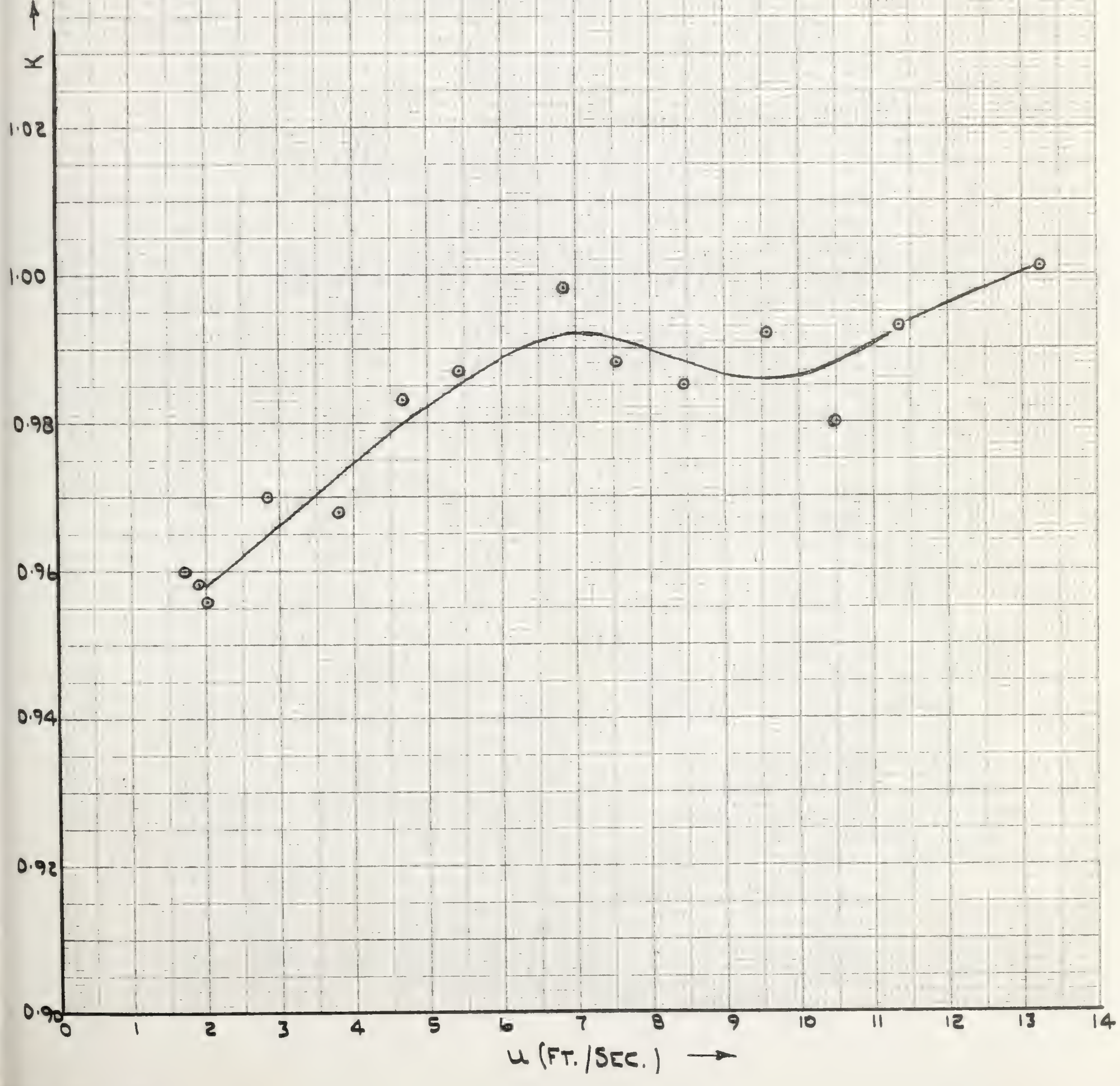
TABLE 1A

Value of Pitot-Static Tube Factor K for the Small Scale Copy of British Standard

U ft./sec.	K
16.69	0.997
19.15	0.999
22.82	1.003
24.87	1.004
27.03	1.005
18.47	1.005
19.66	1.002
16.90	1.001
14.74	1.002
13.24	1.001
11.32	0.993
9.57	0.992
1.95	0.958
2.05	0.956
1.75	0.960
2.86	0.970
3.81	0.968
4.68	0.983
5.46	0.987
6.86	0.998
7.54	0.988
8.47	0.985
10.52	0.980

FIGURE 1A.

THE PITOT - STATIC TUBE FACTOR K FOR THE SMALL SCALE COPY OF THE BRITISH STANDARD.



NOMENCLATURE

g_c	gravitational constant
K	pitot-static tube factor
ΔP	dynamic pressure
U	fluid velocity at measuring point
ρ	fluid density

APPENDIX B

THE MODEL HWB2 HOT-WIRE ANEMOMETER

THE MODEL HWB2 HOT-WIRE ANEMOMETER

Basic Relationships.

The classical work on the heat loss from small wires in a fluid stream is that by L. V. King (8). By a theoretical analysis he obtained the following relationship between the heat loss and fluid properties:

$$\frac{H}{T_w - T} = k + \sqrt{2\pi\rho \, kS \, dU} \quad \text{(B1)}$$

He also deduced that when the cooling stream is air at ordinary pressure there exists a value of the product Ud given by $Ud = 2.01 \times 10^{-5}$ feet^2 per second which represents a critical value below which the above relationship no longer applies.

From a practical standpoint the basic relationship was formulated and confirmed by King (8) and others (12, 13, 14) for the case of air flowing at low speeds normal to the wire but such that Ud is greater than the critical value as:

$$\frac{H}{T_w - T_E} = f_1 \sqrt{U} + f_2 \quad \text{(B2)}$$

In the case of an air flow inclined at an angle less than 45° with the normal to the wire the effective cooling velocity is the component of the velocity vector normal to the wire. The variation of f_1 with temperature difference $T_w - T_E$ was found by King (8) to be little greater than the variation due to experimental errors. The function f_2 was given by King (8) as:

$$f_2 = C_2 + C_3 (T_w - T_E) \quad \text{(B3)}$$

where C_2 and C_3 are constants for a given wire. These findings have been confirmed by Corrsin and Uberoi (27, 28). To avoid confusion it should be pointed out that King's equation used air temperature T rather than the air recovery temperature T_E. The use of T_E in these equations is suggested in Flow Corporation literature (15).

When the wire is at the equilibrium temperature T_w the rate of heat loss from the wire is equal to the rate at which electrical energy is being converted into heat in the wire. Thus:

$$Hl = I^2 R_w \text{ --------------------------- } (B4)$$

Since the slope of the resistance-temperature curve is very nearly a constant over a wide range of temperature for most wire materials it is permissible to relate the temperature difference $T_w - T_E$ to the wire resistance thus:

$$T_w - T_E = \frac{R_w - R_E}{a_o R_o} \text{ --------------------------- } (B5)$$

Substituting from equations B3, B4 and B5 into B2 and replacing f_1 by C_1, a constant for a given wire:

$$I^2 = \frac{1}{a_o R_o}\left(1 - \frac{R_E}{R_w}\right)\left[C_1\sqrt{U} + C_2 + \frac{C_3}{a_o}\left(\frac{R_w}{R_E} - 1\right) + C_3\left(\frac{R_w}{R_E} - 1\right)\left(T_E - T_o\right)\right] \text{ -- } (B6)$$

The Flow Corporation Model HWB2 Hot-Wire Anemometer has been designed to minimize the variation in calibration due to air temperature changes. This is achieved by the constant resistance ratio method of operation in which the ratio $\frac{R_w}{R_E}$ is maintained constant and the heating current I required to maintain this constant ratio used

as a measure of the air velocity. For a given wire operating at a given resistance ratio, equation B6 can be written:

$$I^2 = A\sqrt{U} + B + C\,(T_E - T_o) \qquad \text{(B7)}$$

Flow Corporation literature (15, 16) suggests the use of the following relationship for use with their hot-wire probes:

$$I^2 = A\sqrt{PU} + B + 0.9\left(\frac{T - T_o}{T_o}\right) I_o^{\,2} \qquad \text{(B8)}$$

This relationship can be seen by comparison to be essentially the same as that expressed in equation B7. T_E has been replaced by T, while absolute air pressure has been included under the square root to account for changes in air density due to pressure variation. Justification for the inclusion of this factor is supported by the theoretical relationship B1. It should be noted that B and $I_o^{\,2}$ are not identical due to the non-linearity of the calibration curve below the critical value of Ud. In the present work the calibration curves of hot-wires have been formed by plotting "I^2 + TC" versus $\sqrt{\frac{P}{P_o} U}$, where TC refers to the temperature correction and P_o is a standard pressure of 70 cm. of Hg. Hence:

$$TC = 0.9\left(\frac{T_o - T}{T_o}\right) I_o^{\,2} \qquad \text{(B9)}$$

It must be assumed that the factor 0.9 in this equation strictly applies to Flow Corporation probes HWP-A and HWP-B. The application of this temperature correction to other probes (e.g. the hot-film probe) is not justifiable.

Basic Circuitry.

The basic circuit used in the constant resistance ratio method

of velocity measurement is shown in figure B1. Operation is as follows. The hot-cold switch is closed and only a very small current then flows through the bridge circuit. With such a low heating current the wire temperature is essentially the same as the recovery temperature T_E of the air flowing past it. In this condition the bridge is balanced by adjusting the variable resistance R_3. At the balance point:

$$R_E = \frac{R_3\, R_1}{R_{2c}} \qquad \text{(B10)}$$

The hot-cold switch is now opened and this action also changes the value of the resistance R_2 from R_{2c} to R_{2H}. The relationship between the values of the resistances R_{2c} and R_{2H} is governed by the resistance ratio selected.

With a large heating current now flowing through the bridge circuit, the hot-wire temperature is above that of the air flowing past it. The bridge is again balanced, this time by varying the heating current to the bridge using the variable resistance R_a. This has the effect of varying the temperature and hence the resistance of the wire so as to obtain the balance. At the new balance point:

$$R_w = \frac{R_3 R_1}{R_{2H}} \qquad \text{(B11)}$$

Since R_3 has not been changed in the meantime:

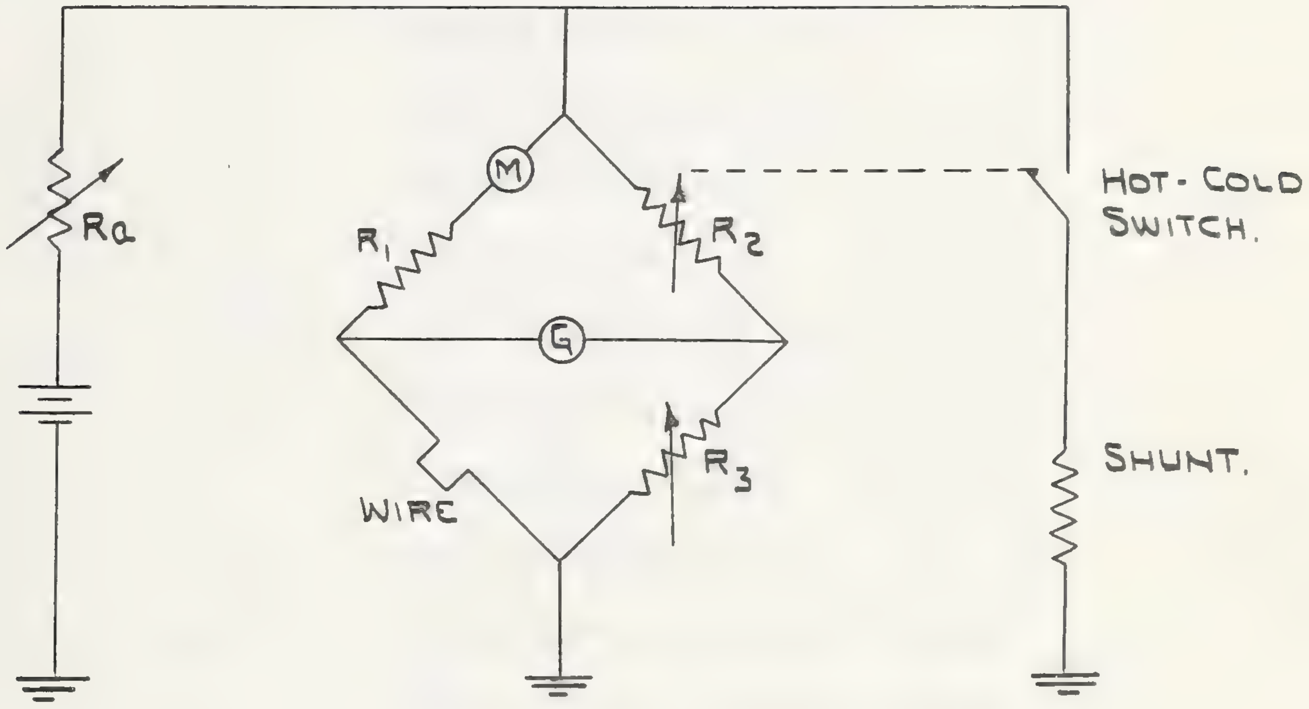
$$\frac{R_w}{R_E} = \frac{R_{2c}}{R_{2H}} \qquad \text{(B12)}$$

Thus by selecting appropriate values for resistances R_{2c} and R_{2H} operation at any desired resistance ratio can be made. After the hot balance has been obtained the current to the wire is measured by a sensitive

potentiometer circuit denoted by M in the circuit diagram, (Fig. B1). This reading is a measure of the air cooling effect.

Adaption for use with the Hot-Film Probe.

The resistance of the unheated film was found to be about 26 ohms while the HWB2 is designed for use with probes of the order of 3 ohms unheated resistance. Balance of the resistance bridge cannot be obtained with wires or films having resistances greater than 15 ohms without modification to the HWB2. The necessary modification consists of inserting a resistance in series with resistor R_1 of the bridge circuit as directed in Flow Corporation literature (16). A 15 ohm resistor was inserted for adaption to use with the hot-film probe.



BASIC CIRCUITRY OF THE HWB-2 HOT-WIRE ANEMOMETER.

FIGURE 18.

NOMENCLATURE

A, B, C, C_1, C_2, C_3	constants; to be evaluated empirically
a_o	temperature coefficient of resistance at T_o
d	wire diameter
f_1	function of wire dimensions and $(T_w - T)$
f_2	function of wire dimensions and $(T_w - T)$
H	heat loss per unit length of wire
I	heating current to wire
I_o	heating current at zero air velocity
k	thermal conductivity
l	length of wire
P	absolute pressure
R_E	wire resistance at T_E
R_w	wire resistance at T_w
R_o	wire resistance at T_o
R_1, R_{2c}, R_{2H}, R_3	resistances in anemometer circuit
S	specific heat at constant volume
T	air temperature
TC	temperature correction to heating current I
T_o	reference temperature
T_E	recovery temperature of air stream
T_w	hot-wire temperature
U	mean flow velocity at measuring point
ρ	density of air

APPENDIX C

EXPERIMENTAL DATA FOR CALIBRATIONS

TABLE 1C

GENERAL DATA

TEST PIPE

Diameter = 6.255 inches
Total Length = 31.5 feet
Distance from throat of entrance venturi to main profile measuring location = 30.33 feet
Diameter of throat of entrance venturi = 1.0 inches

HOT-WIRE PROBES

Wire Material - tungsten
Diameter of stem of HWP-A probe = 0.134 inches
Diameter of stem of HWP-B probe = 0.250 inches
Length of wire for HWP-A and HWP-B probes = 0.044 inches
Diameter of wire for HWP-A and HWP-B probes = .00035 inches
Unheated resistance of wire on HWP-A and HWP-B probes = 1.5 ohms (approx.)

HOT-FILM PROBE

Diameter of stem = 0.134 inches
Unheated resistance of film = 26 ohms (approx.)

MICROMANOMETER

Specific gravity of fluid (N-butyl alcohol)* = 0.8176 at 72°F

* S.G. varies with temperature according to the equation:

$$S.G. = 0.8176 - 0.0004\,(72 - T)$$

TABLE 2C

NO. 1 CALIBRATION OF HWP-A PROBE AGAINST PITOT-STATIC TUBE

Date - Nov. 16
Resistance Ratio - 1.4
Room Temp. - 72°F
Barometric Press. - 70.05 cm. Hg.
Orifice Dia. - 1.544 ins.
Blower Speed - 1050 r.p.m.
I at Zero Air Velocity - 81.75 ma.

1 Test No.	2 W.R.R.C. Rdg.	3 Δh ins. alcohol	4 Air Temp T °R	5 Air Density ρ lbs/ft^3	6 K	7 Air Velocity U ft./sec.	8 $\sqrt{\frac{P}{P_o}U}$ $(\text{ft./sec.})^{\frac{1}{2}}$	9 Current I (ma.)	10 Temp. Correction (ma.)^2	11 I^2 + T.C. (ma.)^2	12 Deviation $I - \bar{I}$ (ma.)
1C	80	.0185	541	.0678	.988	8.55	2.93	97.10	-11	9417	-.07
2C	70	.0154	540	.0679	.991	7.80	2.80	96.45	0	9302	+.09
3C	60	.0120	539	.0680	.992	6.89	2.63	95.32	+11	9097	-.03
4C	50	.0079	539	.0680	.986	5.57	2.36	93.72	+11	8794	-.05
5C	45	.0059	538	.0682	.981	4.79	2.19	92.75	+22	8624	+.03
6C	40	.0048	537	.0683	.977	4.31	2.08	92.00	+33	8496	-.01

By least squares analysis: A = 1095
B = 6220

TABLE 3C

NO. 2 CALIBRATION OF HWP-A PROBE AGAINST PITOT-STATIC TUBE

Date - Nov. 17
Resistance Ratio - 1.4
Room Temp. - 72°F
Barometric Press. - 70.16 cm. Hg.
Orifice Dia. - 1.544 ins.
Blower Speed - 1325 r.p.m.
I at Zero Air Velocity - 81.75 ma.

1 Test No.	2 W.R.R.C. Rdg.	3 Δh ins. alcohol	4 Air Temp T ^{o}R	5 Air Density ρ lbs/ft^3	6 K
7C	100	.0302	543	.0676	.990
8C	90	.0247	542	.0677	.986
9C	80	.0193	541	.0678	.987
10C	70	.0156	540	.0680	.990
11C	60	.0125	539	.0681	.992
12C	50	.0085	539	.0681	.988

7 Air Velocity U ft./sec.	8 $\sqrt{\frac{\rho}{\rho_o} U}$ $(ft./sec.)^{\frac{1}{2}}$	9 Current I (ma)	10 Temp. Correction $(ma)^2$	11 I^2 + T.C. $(ma)^2$	12 Deviation $I - \bar{I}$ (ma)
10.92	3.31	99.77	-33	9921	+.02
9.85	3.14	98.72	-22	9723	-.02
8.73	2.96	97.60	-11	9514	-.04
7.85	2.80	96.67	0	9345	+.01
7.04	2.66	95.92	+11	9211	+.12
5.79	2.41	94.25	+11	8894	-.07

By least squares analysis: A = 1124
B = 6197

TABLE 4C

NO. 3 CALIBRATION OF HWP-A PROBE AGAINST PITOT-STATIC TUBE

Date - Nov. 20
Resistance Ratio - 1.4
Room Temp. - 72°F
Barometric Press. - 69.87 cm. Hg.
Orifice Dia. - 1.544 ins.
Blower Speed - 1570 r.p.m.
I at Zero Air Velocity - 81.75 ma.

1 Test No.	2 W.R.R.C. Rdg.	3 Δh ins. alcohol	4 Air Temp. T °R	5 Air Density ρ lbs/ft^3	6 K
13C	116	.0422	546	.0670	1.000
14C	110	.0382	545	.0671	.998
15C	100	.0313	544	.0672	.992
16C	90	.0254	543	.0674	.986
17C	80	.0198	541	.0676	.987
18C	70	.0156	540	.0677	.990
19C	60	.0122	539	.0678	.992

7 Air Velocity U ft./sec.	8 $\sqrt{\frac{\rho}{\rho_0} U}$ (ft./sec.)$^{\frac{1}{2}}$	9 Current I (ma)	10 Temp. Correction (ma)^2	11 I^2 + T.C. (ma)^2	12 Deviation $I - \bar{I}$ (ma)
13.05	3.61	100.69	-67	10071	0
12.38	3.51	100.20	-56	9984	+.08
11.18	3.34	99.07	-44	9770	-.10
10.00	3.16	98.15	-33	9600	-.01
8.85	2.97	96.97	-11	9392	-.06
7.86	2.80	96.00	0	9216	-.03
6.95	2.63	95.10	+11	9054	+.05

By least squares analysis: A = 1050
B = 6282

TABLE 5C

NO. 4 CALIBRATION OF HWP-A PROBE AGAINST PITOT-STATIC TUBE

Date	-	Dec. 6
Resistance Ratio	-	1.4
Room Temp.	-	72°F
Barometric Press.	-	70.25 cm. Hg.
Orifice Dia.	-	1.544 ins.
Blower Speed	-	1350 r.p.m.
I at Zero Air Velocity	-	81.75 ma.

1 Test No.	2 W.R.R.C. Rdg.	3 Δh ins. alcohol	4 Air Temp. T °R	5 Air Density ρ lbs/ft^3	6 K
20C	100	.0318	545	.0675	.992
21C	90	.0246	543	.0678	.986
22C	80	.0195	541	.0680	.987
23C	76	.0177	541	.0680	.988
24C	68	.0146	539.5	.0682	.991
25C	64	.0131	539.5	.0682	.992
26C	59	.0111	539.5	.0682	.991
27C	55	.0098	539	.0683	.990
28C	51	.0082	539	.0683	.987

7 Air Velocity U ft./sec.	8 $\sqrt{\frac{P\ U}{P_o}}$ (ft/sec)$^{\frac{1}{2}}$	9 Current I (ma)	10 Temp. Correction (ma)^2	11 I^2 + T.C. (ma)^2	12 Deviation $I - \bar{I}$ (ma)
11.22	3.36	99.05	-56	9754	
9.84	3.14	97.95	-33	9559	
8.76	2.97	97.27	-11	9451	
8.35	2.89	96.97	-11	9392	
7.58	2.76	96.02	+5	9225	-.12
7.17	2.68	95.62	+5	9148	-.08
6.60	2.57	95.05	+5	9038	-.07
6.20	2.49	94.40	+11	8923	-.16
5.66	2.38	94.00	+11	8846	+.08

By least squares analysis of points 24C - 28C inc. and 38C - 40C inc.:

A = 1094
B = 6228

TABLE 6C

NO. 5 CALIBRATION OF HWP-A PROBE AGAINST PITOT-STATIC TUBE

Date - Dec. 9
Resistance Ratio - 1.4
Room Temp. - 72°F
Barometric Press. - 70.31 cm. Hg.
Orifice Dia. - 1.544 ins.
Blower Speed - 1550 r.p.m.
I at Zero Air Velocity - 81.75 ma.

1 Test No.	2 W.R.R.C. Rdg.	3 Δh ins. alcohol	4 Air Temp. T °R	5 Air Density ρ lbs/ft^3	6 K
29C	115	.0414	548	.0672	1.000
30C	110	.0377	547	.0673	.997
31C	105	.0347	546	.0674	.995
32C	100	.0315	545	.0675	.992
33C	95	.0283	544	.0676	.989
34C	90	.0259	543	.0677	.987
35C	86	.0234	542	.0679	.986
36C	78	.0197	541	.0680	.987
37C	74	.0175	540	.0681	.989
38C	68	.0144	539.5	.0682	.991
39C	63	.0125	539.5	.0682	.992
40C	55	.0097	539	.0683	.990

7 Air Velocity U ft./sec.	8 $\sqrt{\frac{\rho}{\rho_0} U}$ (ft./sec.)$^{\frac{1}{2}}$	9 Current I (ma)	10 Temp. Correction (ma)^2	11 I^2 + T.C. (ma)^2	12 Deviation I - $\bar{I}$ (ma)
12.90	3.60	100.05	-89	9921	
12.29	3.51	99.62	-78	9847	
11.76	3.44	99.27	-67	9788	
11.18	3.35	99.07	-56	9759	
10.57	3.26	98.57	-44	9671	
10.09	3.18	98.17	-33	9605	
9.59	3.10	97.70	-22	9523	
8.80	2.97	97.17	-11	9430	
8.28	2.88	96.77	0	9363	
7.52	2.75	96.15	+5	9250	+.06
7.01	2.65	95.75	+5	9172	+.23
6.17	2.49	94.55	+11	8951	+.01

By least squares analysis of points 24C - 28C inc. and 38C - 40C inc.:

A = 1094
B = 6228

TABLE 7C

SUMMARY OF TRIAL AND ERROR ANALYSIS OF PROFILES 1 to 5 TO OBTAIN CALIBRATION OF HWP-A PROBE AT LOW AIR SPEEDS

1 Profile No.	2 Orifice* ΔP_o cms. H_2O	3 Air Temp. T ^oR	4 Air Press P cm. Hg.	5 Air Density ρ lbs/ft^3	6 Vol. Flow Rate Q_o ft^3/sec	7 Av. Vel $\bar{U}_o$ ft/sec
1 HW	5.8	537	71.00	.0693	.0667	.313
2 HW	12.0	537	69.82	.0681	.0968	.454
3 HW	19.6	539	69.96	.0680	.124	.580
4 HW	33.1	539	71.00	.0690	.160	.748
5 HW	55.0	541	71.00	.0687	.206	.967

8 I^2 + T.C. maximum $(ma)^2$	9 Trial No.	10 Assumed $\frac{\bar{U}}{U_m}$	11 $U_{mo} = \bar{U}_o \times \frac{U_m}{\bar{U}}$ ft./sec.	12 $\sqrt{\frac{P}{P_o}}\, U_{mo}$ $(ft/sec)^{\frac{1}{2}}$	13 By Graph. Integration Q_p $ft^3/sec.$	14 $\bar{U}_p$ ft./sec.
7004	1	.80	.391	.625	.0676	.317
7042		.80	.568	.754	.0910	.426
7159		.80	.725	.851	.113	.532
7341		.80	.936	.968	.157	.739
7434		.80	1.210	1.100	.200	.937
	2	.666	.470	.690	.0709	.332
		.805	.565	.751	.0952	.446
		.765	.759	.871	.1178	.553
		.749	.999	1.007	.1636	.768
		.808	1.197	1.101	.2065	.973

15 Trial No.	16 U_{mp} ft./sec.	17 $\left(\frac{\bar{U}}{U_m}\right)_p$
1 (contd.)	.476	.666
	.530	.805
	.697	.765
	.986	.749
	1.160	.808
2 (contd.)	.494	.674
	.553	.808
	.726	.761
	1.020	.753
	1.198	.811

18 Correct $\frac{\bar{U}}{U_m}$	19 $U_{mo} = \bar{U}_o \times \frac{U_m}{\bar{U}}$ ft/sec	20 Percent Error $\frac{U_{mp} - U_{mo}}{U_{mo}} \times 100$
.674	.465	+6.4
.808	.562	-1.6
.761	.763	-4.7
.753	.994	+2.6
.811	1.190	+0.7

* Orifice dia. = 3/8"

TABLE 8C

CALIBRATION OF HWP-A PROBE AT VARIOUS RESISTANCE RATIOS

Date - Nov. 21
Room Temp. - 72°F
Barometric Press. - 70.95 cm. Hg.
Orifice Dia. - 1.544 ins.

1	2	3	4	5	6	7
Test No.	Blower Speed r.p.m.	W.R.R.C. Rdg.	Air Temp. T $^\circ$R	Current I		
				Res.Ratio = 1.1 ma.	Res. Ratio = 1.2 ma.	Res.Ratio =1.3 ma.
41C	0	0	539	46.25	62.80	73.72
42C	1350	55	539	53.70	73.00	85.75
43C	1350	70	539	54.45	74.27	87.30
44C	1350	80	540	54.87	75.00	88.17
45C	1350	90	542	55.02	75.52	88.90
46C	1350	100	543	55.62	76.27	89.52
47C	1550	110	544	55.80	76.60	90.07

8	9	10	11	12	13	14
Current I Res. Ratio =1.4 ma.	Temp. Correction $(ma)^2$	I^2 + T.C.				$\sqrt{\frac{P}{P_o}U}$ $(ft./sec.)^{\frac{1}{2}}$
		Res. Ratio =1.1 $(ma)^2$	Res. Ratio =1.2 $(ma)^2$	Res. Ratio =1.3 $(ma)^2$	Res. Ratio =1.4 $(ma)^2$	
81.68	+11	2150	3955	5446	6683	0
94.52	+11	2894	5340	7364	8945	2.49
96.37	+11	2975	5527	7633	9299	2.81
97.22	0	3011	5625	7774	9452	2.95
98.20	-22	3006	5681	7882	9622	3.11
98.87	-33	3060	5784	7981	9743	3.22
99.75	-44	3069	5824	8068	9906	3.36

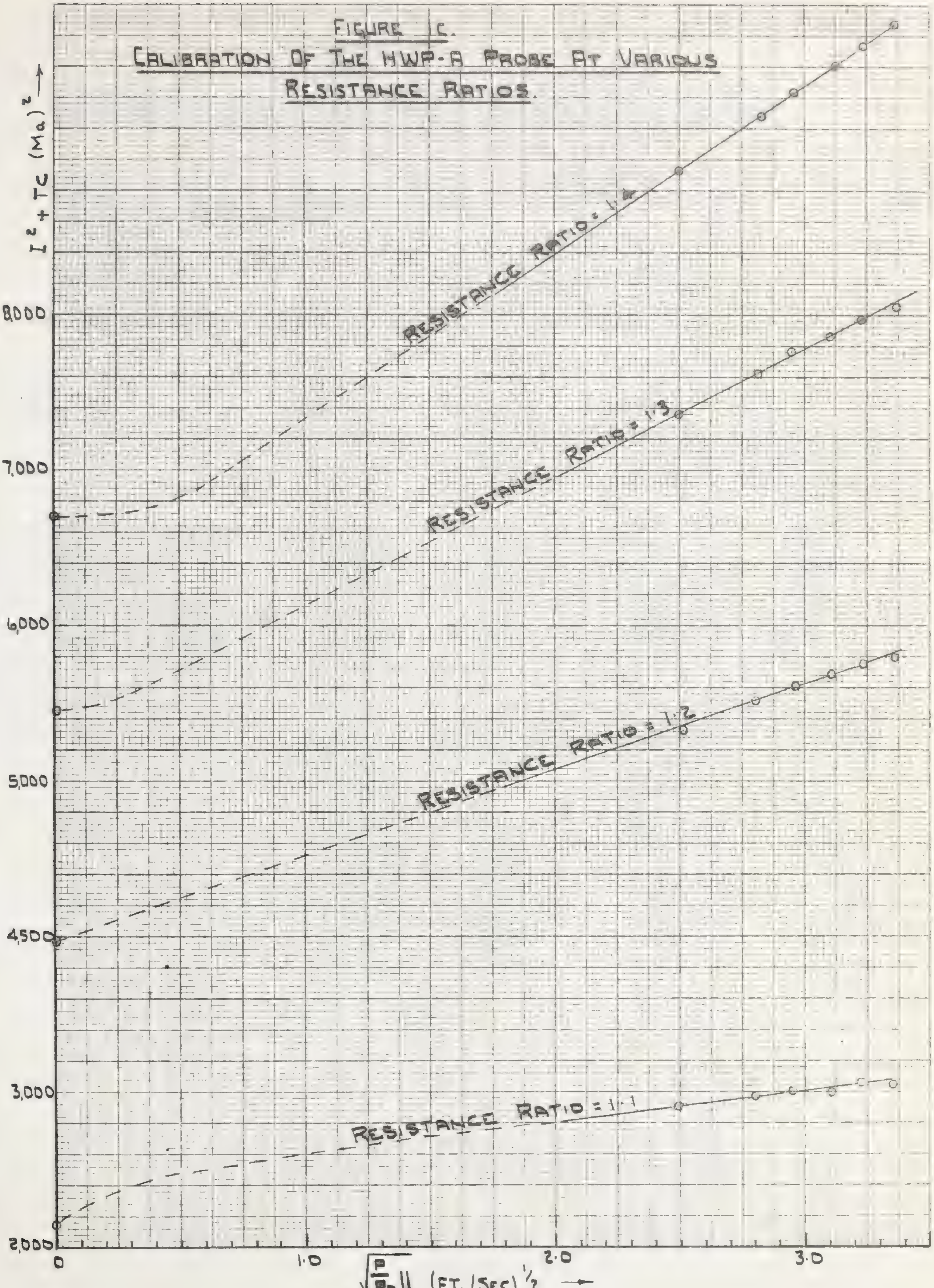


FIGURE 1c.
CALIBRATION OF THE HWP-A PROBE AT VARIOUS RESISTANCE RATIOS.

TABLE 9C

CALIBRATION OF HWP-B PROBE AGAINST HWP-A PROBE AT LOW AIR SPEEDS

Date - Dec. 10
Resistance Ratio for HWP-A Probe - 1.4
Resistance Ratio for HWP-B Probe - 1.4
Orifice Dia. - 0.375 ins.*
Blower Speed - 910 r.p.m.
Room Temp. - 72°F
Barometric Press. - 70.85 cm. Hg.

1 Test No.	2 Air Temp. T °R	3 HWP-A Current (ma)	4 Temp. Correction $(\text{ma})^2$	5 HWP-A I^2 + T.C. $(\text{ma})^2$	6 $\sqrt{\frac{P}{P_o}U}$ $(\text{ft./sec.})^{\frac{1}{2}}$
48C	539	81.70	+11	6686	0
49C	539	83.40	+11	6967	0.67
50C	539	85.05	+11	7244	0.93
51C	539	86.00	+11	7407	1.08
52C	539	89.00	+11	7932	1.56
53C	539	90.92	+11	8278	1.87

7 HWP-B Current (ma)	8 HWP-B I^2 + T.C. $(\text{ma})^2$	9 Deviation $I - \bar{I}$ (ma)
92.02	8479	+.11
94.60	8960	-.01
96.87	9394	-.08
98.15	9644	+.26
102.60	10538	+.05
105.12	11061	+.05

*Orifice dia. for test 53C = 1.544 ins.

TABLE 10C

CALIBRATION OF HWP-B PROBE AGAINST PITOT-STATIC TUBE

Date - Dec. 10
Resistance Ratio - 1.4
Room Temp. - 72°F
Barometric Pressure - 70.85 cm. Hg.
Orifice Dia. - 1.544 ins.
Blower Speed - 1350 r.p.m.*

1 Test No.	2 W.R.R.C. Rdg.	3 Δh ins. alcohol	4 Air Temp. T °R	5 Air Density ρ lbs/ft^3	6 K
54C	51	.0082	539	.0688	.987
55C	71	.0168	540	.0686	.990
56C	91	.0244	543	.0683	.986
57C	110	.0379	546	.0680	.997

7 Air Velocity U ft./sec.	8 $\sqrt{\frac{P\,U}{P_o}}$ (ft./sec.)$^{\frac{1}{2}}$	9 Current I (ma)	10 Temp. Correction (ma)^2	11 I^2 + T.C. (ma)^2	12 Deviation $I - \bar{I}$ (ma)
5.64	2.39	109.37	+11	11973	+.05
8.10	2.86	113.02	0	12774	-.07
9.75	3.14	115.35	-33	13273	-.07
12.24	3.52	118.37	-67	13944	-.03

From plot of calibration: A = 1760
B = 7760

*Blower speed for test 57C = 1550 r.p.m.

TABLE 11C

NO. 1 CALIBRATION OF HOT-FILM PROBE AGAINST PITOT-STATIC TUBE

Date - Dec. 12
Resistance Ratio - 1.1
Room Temp. - 72°F
Barometric Press. - 69.90 cm. Hg.
Orifice Dia. - 1.544 ins.

1 Test No.	2 Blower Speed r.p.m.	3 W.R.R.C. Rdg.	4 Δh ins. alcohol	5 Air Temp. T °R	6 Air Density ρ lbs/ft^3
58C	0	0	0	539	.0679
59C	1050	39	.0039	539	.0679
60C	1050	45	.0049	539	.0679
61C	1350	55	.0079	539	.0679
62C	1350	65	.0113	539	.0679
63C	1350	78	.0177	540	.0677
64C	1350	87	.0226	543	.0674
65C	1350	95	.0273	544	.0673
66C	1350	100	.0302	544	.0673

7 K	8 Air Velocity U ft/sec.	9 $\sqrt{\frac{P}{P_o}U}$ (ft./sec.)$^{\frac{1}{2}}$	10 Current I (ma)	11 I^2 (ma)^2	12 Deviation $I - \bar{I}$ (ma)
-	0	0	31.47	991	-.09
.974	3.89	1.97	35.60	1267	-.04
.978	4.36	2.09	35.92	1290	+.04
.986	5.57	2.36	36.30	1318	-.08
.991	6.68	2.58	36.85	1358	+.06
.988	8.37	2.89	37.32	1393	-.06
.986	9.45	3.07	37.75	1425	+.04
.988	10.39	3.22	38.00	1444	+.01
.990	10.94	3.30	38.17	1457	+.04

From plot of calibration: $A = 139$
$B = 996$

TABLE 12C

NO. 2 CALIBRATION OF HOT-FILM PROBE AGAINST HWP-A PROBE AT LOW AIR SPEEDS

Date - Dec. 15
Resistance Ratio for Hot-Film Probe - 1.1
Resistance Ratio for HWP-A Probe - 1.4
Room Temp. - 73°F
Barometric Press. - 70.95 cm. Hg.
Orifice Dia. - 0.375 ins.*
Blower Speed - 910 r.p.m.

1 Test No.	2 Air Temp. T °R	3 HWP-A Current (ma)	4 Temp. Correction $(ma)^2$	5 HWP-A I^2 + T.C. $(ma)^2$
67C	539	81.75	+11	6694
68C	539	83.12	+11	6919
69C	539	84.25	+11	7109
70C	539	85.25	+11	7278
71C	539	87.25	+11	7622
72C	539	90.87	+11	8268

6 $\sqrt{\frac{P\ U}{P_o}}$ $(ft/sec)^{\frac{1}{2}}$	7 Hot-Film Current (ma)	8 Hot-Film I^2 $(ma)^2$	9 Deviation $I - \bar{I}$ (ma)
0	30.77	947	+.05
0.63	31.90	1018	-.13
0.80	32.47	1055	+.09
0.96	32.60	1063	-.10
1.27	33.37	1113	+.05
1.86	34.50	1190	+.07

*Orifice dia. for test 72C = 1.544 ins.

TABLE 13C

NO. 2 CALIBRATION OF HOT-FILM PROBE AGAINST PITOT-STATIC TUBE

Date - Dec. 15
Resistance Ratio - 1.1
Room Temp. - 73°F
Barometric Press. - 70.95 cm. Hg.
Orifice Dia. - 1.544 ins.

1 Test No.	2 Blower Speed r.p.m.	3 W.R.R.C. Rdg.	4 Δh ins. alcohol	5 Air Temp. T °R	6 Air Density ρ lbs/ft^3
73C	1250	45	.0060	539	.690
74C	1350	55	.0089	540	.687
75C	1350	68	.0146	540	.687
76C	1350	80	.0186	542	.685
77C	1350	90	.0236	543	.684

7 K	8 Air Velocity U ft./sec.	9 $\sqrt{\frac{P}{P_o}}\,U$ (ft./sec.)$^{\frac{1}{2}}$	10 Current I (ma)	11 I^2 (ma)	12 Deviation $I - \bar{I}$ (ma)
.981	4.80	2.21	35.05	1229	-.05
.988	5.88	2.44	35.62	1268	+.09
.991	7.55	2.77	36.12	1305	-.01
.988	8.52	2.94	36.37	1323	-.06
.986	9.60	3.12	36.77	1352	+.02

By least squares analysis: A = 130.4
B = 944.1

TABLE 14C

SUMMARY OF RESULTS OF LEAST SQUARES ANALYSIS OF CALIBRATIONS

1 Probe	2 Calibration No.	3 Test Points Analyzed	4 A	5 B $(ma)^2$
HWP-A	1	1C-6C	1095	6220
HWP-A	2	7C-12C	1124	6197
HWP-A	3	13C-19C	1050	6282
HWP-A	4 and 5	24C-28C 38C-40C	1094	6228
HWP-A	4 and 5	24C-28C 38C-40C 5 Profile pts.	1094	6229
HWP-B	-	48C-57C	1760	7760*
Hot-Film	1	58C-66C	139	996*
Hot-Film	2	67C-77C	130	944

*Values of A and B estimated from calibration plot and not by least squares analysis.

TABLE 15C

COMPARISON OF ERRORS FOR VELOCITY MEASURING DEVICES

Velocity ft/sec	Percentage Error in Velocity Pitot-Static Tube %	HWP-A Probe %	Hot-Film Probe %
0.5	110	5.2	16.5
1.0	35	3.7	12.0
2.0	10	2.7	8.8
4.0	2.5	2.0	6.4
6.0	1.1	1.7	5.3
8.0	0.6	1.5	4.7
10.0	0.4	1.4	4.3
12.0	0.3	1.3	4.0

NOMENCLATURE

A, B	constants, to be evaluated empirically
Δh	dynamic head, read by means of the micromanometer
I	heating current to wire
$\bar{I}$	heating current requirement according to calibration curve
K	pitot-static tube factor
P	absolute pressure
P_o	reference pressure (70 cm. Hg.)
ΔP_o	pressure drop across the orifice
Q_o	volumetric rate of flow of air at air stream conditions of temperature and pressure, calculated from the orifice pressure drop
Q_p	volumetric rate of flow of air at air stream conditions of temperature and pressure, estimated by integration of the velocity profile
T	air temperature
T.C.	temperature correction
U	mean flow velocity at measuring point
U_m	mean flow velocity at pipe axis
U_{mo}	velocity at pipe axis estimated from the flow rate measured with the orifice
U_{mp}	velocity at pipe axis measured with the hot-wire probe
$\bar{U}$	average velocity of flow in pipe
$\bar{U}_o$	average velocity of flow in pipe obtained from Q_o
$\bar{U}_p$	average velocity of flow in pipe obtained from Q_p
W.R.R.C.	weight rate recorder-controller reading
ρ	density of air

APPENDIX D

EXPERIMENTAL DATA FOR VELOCITY PROFILES

TABLE 1D

Profile No. 1 HW.

Date	- Dec. 7	Blower Speed	- 910 r.p.m.
Room Temp.	- 74°F	Orifice Dia.	- 0.375 ins.
Barometric Press.	- 71.0 cm. Hg.	Orifice Diff.Press.	- 5.8 cm. H_2O
Flowing Air Temp.	- 537 °R	Air Density	- .0693 lbs/ft^3
Resistance Ratio	- 1.4	Vol.Rate of Flow Q_o	- .0667 ft^3/sec
Temp. Correction	- + 33 (ma)^2	Average Velocity $\bar{U}_o$	- .313 ft/sec
I at Zero Air Velocity	- 81.67 (ma)	Reynolds No. Re.	- 925

1 Dist.from wall ins.	2 Radius r ins.	3 Current I (ma)	4 I^2 + T.C. (ma)^2	5 $\sqrt{\frac{P}{P_o}}\,U$ (ft/sec)$^{\frac{1}{2}}$	6 Air Velocity U ft/sec	7 $\frac{U}{U_m}$
.067	3.060	81.82	6728	0.300	.089	.180
.167	2.960	82.07	6768	.400	.158	.320
.267	2.860	82.25	6798	.470	.218	.441
.367	2.760	82.45	6831	.520	.266	.539
.467	2.660	82.57	6851	.550	.298	.603
.627	2.500	82.70	6873	.585	.337	.682
.937	2.190	82.80	6889	.603	.358	.725
1.247	1.880	82.95	6913	.625	.385	.780
1.567	1.560	83.10	6938	.648	.414	.839
1.877	1.250	83.22	6958	.666	.437	.885
2.187	0.940	83.32	6975	.681	.457	.926
2.497	0.630	83.42	6991	.696	.476	.965
2.817	0.310	83.50	7004	.708	.494	1.000
3.127	0.000	83.50	7004	.708	.494	1.000
3.437	0.309	83.50	7004	.708	.494	1.000
3.757	0.629	83.42	6991	.696	.476	.965
4.067	0.939	83.37	6983	.688	.466	.944
4.377	1.249	83.25	6963	.670	.442	.895
4.687	1.559	83.10	6938	.648	.414	.839
5.007	1.879	83.00	6922	.633	.395	.800
5.317	2.189	83.87	6899	.611	.368	.745
5.627	2.499	82.60	6856	.555	.304	.616
5.787	2.659	82.50	6839	.535	.282	.571
5.887	2.759	82.37	6818	.500	.246	.498
5.987	2.859	82.25	6798	.470	.218	.441

TABLE 2D

Profile No. 2 HW.

Date	- Dec. 5	Orifice Dia.	- 0.375 ins.
Room Temp.	- 73°F	Orifice Diff.Press	- 12.0 cm. H_2O
Barometric Press.	- 69.82 cm. Hg.	Air Density	- .0681 lbs/ft^3
Flowing Air Temp.	- 537°R	Vol.Rate of Flow Q_o	- .0968 ft^3/sec
Resistance Ratio	- 1.4	Average Vel. $\bar{U}_o$	- .454 ft/sec
Temp. Correction	- +33 $(ma)^2$	Reynolds No. Re_o	- 1320
I at Zero Air Velocity	- 81.75 (ma)		
Blower Speed	- 910 r.p.m.		

1 Dist.from wall ins.	2 Radius r ins.	3 Current I (ma)	4 I^2 + T.C. $(ma)^2$	5 $\sqrt{\frac{P}{P_o}}\,U$ $(ft/sec)^{\frac{1}{2}}$	6 Air Velocity U ft./sec.	7 $\frac{U}{U_m}$
.067	3.060	81.87	6736	.330	.109	.195
.167	2.960	82.00	6757	.380	.144	.205
.267	2.860	82.50	6839	.535	.287	.514
.367	2.760	82.67	6868	.575	.332	.594
.467	2.660	83.00	6922	.633	.402	.720
.627	2.500	83.30	6972	.679	.462	.828
.937	2.190	83.67	7033	.734	.540	.967
1.247	1.880	83.50	7004	.708	.502	.899
1.567	1.560	83.70	7038	.739	.547	.980
1.877	1.250	83.75	7046	.747	.559	1.000
2.187	0.940	83.62	7024	.726	.528	.945
2.497	0.630	83.72	7042	.743	.553	.990
2.817	0.310	83.75	7046	.747	.559	1.000
3.127	0.000	83.70	7038	.739	.547	.980
3.437	0.309	83.75	7046	.747	.559	1.000
3.757	0.629	83.75	7046	.747	.559	1.000
4.067	0.939	83.70	7038	.739	.547	.980
4.377	1.249	83.77	7049	.749	.562	1.005
4.687	1.559	83.75	7046	.747	.559	1.000
5.007	1.879	83.70	7038	.739	.547	.980
5.317	2.189	83.77	7049	.749	.562	1.005
5.627	2.499	83.25	6963	.670	.450	.806
5.787	2.659	83.05	6929	.639	.409	.732
5.887	2.759	82.67	6868	.575	.332	.594
5.987	2.859	82.25	6798	.470	.222	.397

TABLE 3D

Profile No. 3 HW.

Date - Dec. 5
Room Temp. - 73°F
Barometric Press. - 69.96 cm.Hg.
Flowing Air Temp. - 539°R
Resistance Ratio - 1.4
Temp.Correction - + 11 $(\text{ma})^2$
I at Zero Air Velocity - 81.75 (ma)
Blower Speed - 910 r.p.m.

Orifice Dia. - 0.375 ins.
Orifice Diff.Press. - 19.6 cm. H_2O
Air Density - .0680 $\text{lbs}/\text{ft.}^3$
Vol.Rate of Flow Q_o - .124 ft^3/sec
Average Velocity U_o - .580 ft/sec.
Reynolds No. Re. - 1690

1 Dist. from wall ins.	2 Radius r ins.	3 Current I (ma)	4 I^2 + T.C. $(\text{ma})^2$	5 $\sqrt{\frac{P}{P_o}U}$ $(\text{ft/sec})^{\frac{1}{2}}$	6 Air Velocity U ft/sec.	7 $\frac{U}{U_m}$
.067	3.060	82.00	6735	.330	.109	.150
.167	2.960	82.25	6776	.425	.181	.249
.267	2.860	82.75	6859	.560	.314	.432
.367	2.760	83.15	6924	.635	.403	.555
.467	2.660	83.62	7002	.706	.498	.686
.627	2.500	83.92	7054	.754	.568	.782
.937	2.190	84.27	7112	.806	.650	.895
1.247	1.880	84.40	7134	.826	.682	.939
1.567	1.560	84.50	7151	.842	.709	.976
1.877	1.250	84.50	7151	.842	.709	.976
2.187	0.940	84.50	7151	.842	.709	.976
2.497	0.630	84.50	7151	.842	.709	.976
2.817	0.310	84.52	7154	.845	.714	.983
3.127	0.000	84.55	7159	.850	.722	.995
3.437	0.309	84.57	7162	.852	.726	1.000
3.757	0.629	84.57	7162	.852	.726	1.000
4.067	0.939	84.50	7151	.842	.709	.976
4.377	1.249	84.55	7151	.842	.709	.976
4.687	1.559	84.50	7151	.842	.709	.976
5.007	1.879	84.50	7151	.842	.709	.976
5.317	2.189	84.25	7110	.805	.648	.892
5.627	2.499	84.00	7067	.766	.587	.809
5.787	2.659	83.55	6991	.696	.484	.666
5.887	2.759	83.12	6920	.631	.398	.548
5.987	2.859	82.75	6849	.550	.302	.416

TABLE 4D

Profile No. 4 HW

Date - Dec. 7
Room Temp. - 74°F
Barometric Press. - 71.0 cm.Hg.
Flowing Air Temp. - 539°R
Resistance Ratio - 1.4
Temp. Correction - + 11 (ma)^2
I at Zero Air Velocity - 81.67 (ma)
Blower Speed - 910 r.p.m.

Orifice Dia. - 0.375 ins.
Orifice Diff.Press. - 33.1 cm. H_2O
Air Density - .0690 lbs/ft^3
Vol. Rate of Flow Q_o - .160 ft^3/sec
Average Velocity $\bar{U}_o$ - .748 ft/sec
Reynolds No. Re. - 2210

1 Dist.from wall ins.	2 Radius r ins.	3 Current I (ma)	4 I^2 + T.C. $(ma)^2$	5 $\sqrt{\frac{P}{P_o} U}$ $(\text{ft/sec})^{\frac{1}{2}}$	6 Air Velocity U ft/sec	7 $\frac{U}{U_m}$
.067	3.060	82.37	6796	.460	.209	.197
.167	2.960	82.92	6886	.600	.355	.348
.267	2.860	83.32	6952	.660	.430	.421
.367	2.760	83.75	7024	.726	.520	.510
.467	2.660	84.20	7101	.797	.625	.613
.627	2.500	84.62	7171	.860	.730	.716
.937	2.190	85.12	7256	.937	.865	.848
1.247	1.880	85.42	7308	.985	.955	.936
1.567	1.560	85.62	7341	1.018	1.020	1.000
1.877	1.250	85.62	7341	1.018	1.020	1.000
2.187	0.940	85.62	7341	1.018	1.020	1.000
2.497	0.630	85.62	7341	1.018	1.020	1.000
2.817	0.310	85.62	7341	1.018	1.020	1.000
3.127	0.000	85.62	7341	1.018	1.020	1.000
3.437	0.309	85.62	7341	1.018	1.020	1.000
3.757	0.629	85.62	7341	1.018	1.020	1.000
4.067	0.939	85.62	7341	1.018	1.020	1.000
4.377	1.249	85.62	7341	1.018	1.020	1.000
4.687	1.559	85.57	7332	1.009	1.002	.983
5.007	1.879	85.50	7321	.998	.982	.963
5.317	2.189	85.25	7278	.959	.906	.889
5.627	2.499	84.70	7185	.874	.753	.738
5.787	2.659	84.10	7084	.781	.601	.590
5.887	2.759	83.80	7032	.733	.529	.519
5.987	2.859	83.25	6941	.650	.415	.407

TABLE 5D

Profile No. 5 HW.

Date - Dec. 7
Room Temp. - 74°F
Barometric Press. - 71.0 cm.Hg.
Flowing Air Temp. - 541°R
Resistance Ratio - 1.4
Temp. Correction - -11 $(ma)^2$
I at Zero Air Velocity - 81.67 ma
Blower Speed - 910 r.p.m.

Orifice Dia. - 0.375 ins.
Orifice Diff.Press. - 55.0 cm. H_2O
Vol. Rate of Flow Q_o - .206 ft^3/sec
Average Velocity $\bar{U}_o$ - .967 ft/sec
Air Density - .0687 lb/ft^3
Reynolds No. Re. - 2840

1 Dist.from wall ins.	2 Radius r ins.	3 Current I ma	4 I^2 + T.C. $(ma)^2$	5 $\sqrt{\frac{P}{P_o}}\ U$ $(ft/sec)^{\frac{1}{2}}$	6 Air Velocity U ft/sec	7 $\frac{U}{U_m}$
.067	3.060	83.12	6898	.611	.368	.306
.167	2.960	84.07	7058	.757	.565	.469
.267	2.860	84.55	7138	.830	.679	.563
.367	2.760	84.90	7197	.884	.770	.639
.467	2.660	85.25	7256	.938	.867	.720
.627	2.500	85.50	7299	.977	.940	.780
.937	2.190	86.07	7398	1.068	1.123	.932
1.247	1.880	86.20	7419	1.087	1.167	.969
1.567	1.560	86.25	7428	1.094	1.179	.979
1.877	1.250	86.30	7437	1.102	1.198	.995
2.187	0.940	86.25	7428	1.094	1.179	.979
2.497	0.630	86.30	7437	1.102	1.198	.995
2.817	0.310	86.25	7428	1.094	1.179	.979
3.127	0.000	86.32	7440	1.106	1.205	1.000
3.437	0.309	86.25	7428	1.094	1.179	.979
3.757	0.629	86.25	7428	1.094	1.179	.979
4.067	0.939	86.32	7440	1.106	1.205	1.000
4.377	1.249	86.25	7428	1.094	1.179	.979
4.687	1.559	86.25	7428	1.094	1.179	.979
5.007	1.879	86.15	7410	1.080	1.149	.954
5.317	2.189	85.87	7362	1.035	1.059	.878
5.627	2.499	85.62	7319	.995	.975	.809
5.787	2.659	85.25	7256	.938	.867	.720
5.887	2.759	85.05	7222	.907	.811	.673
5.987	2.859	84.67	7158	.849	.711	.590

TABLE 6D

Profile No. 6 HW.

Date - Dec. 8
Room Temp. - 73°F
Barometric Press. - 70.82 cm.Hg.
Flowing Air Temp. - 537°R
Resistance Ratio - 1.4
Temp. Correction - +33 $(ma)^2$
I at Zero velocity - 81.67 ma

Blower Speed - 910 r.p.m.
Orifice Dia. - 0.75 ins.
Air Density - .0690 lbs/ft^3
Vol. Rate of Flow Q_p - .397 ft^3/sec
Average Velocity $\bar{U}_p$ - 1.864 ft/sec
Reynolds No. Re. - 5490

1 Dist.from wall ins.	2 Radius r ins.	3 Current I ma.	4 I^2 + T.C. $(ma)^2$	5 $\sqrt{\frac{P}{P_o}}\,U$ $(ft/sec)^{\frac{1}{2}}$	6 Air Velocity U ft/sec	7 $\frac{U}{U_m}$
.067	3.060	84.55	7182	.870	.749	.318
.167	2.960	85.50	7343	1.019	1.026	.436
.267	2.860	86.25	7472	1.137	1.280	.545
.367	2.760	86.82	7570	1.226	1.486	.632
.467	2.660	87.32	7658	1.305	1.685	.717
.627	2.500	87.82	7744	1.384	1.891	.805
.937	2.190	88.12	7798	1.433	2.030	.864
1.247	1.880	88.50	7865	1.493	2.205	.939
1.567	1.560	88.60	7883	1.511	2.260	.962
1.877	1.250	88.77	7913	1.539	2.340	.996
2.187	0.940	88.77	7913	1.539	2.340	.996
2.497	0.630	88.77	7913	1.539	2.340	.996
2.817	0.310	88.77	7913	1.539	2.340	.996
3.127	0.000	88.80	7918	1.543	2.350	1.000
3.437	0.309	88.77	7913	1.539	2.340	.996
3.757	0.629	88.77	7913	1.539	2.340	.996
4.067	0.939	88.77	7913	1.539	2.340	.996
4.377	1.249	88.75	7910	1.537	2.335	.994
4.687	1.559	88.62	7886	1.512	2.260	.962
5.007	1.879	88.47	7861	1.490	2.195	.934
5.317	2.189	88.25	7822	1.456	2.100	.894
5.627	2.499	87.75	7733	1.373	1.865	.794
5.787	2.659	87.40	7672	1.319	1.720	.732
5.887	2.759	86.95	7593	1.246	1.535	.653
5.987	2.859	86.32	7484	1.146	1.298	.552

TABLE 7D

Profile No. 7 HW.

Date - Dec. 8
Room Temp. - 73^{o}F
Barometric Press. - 70.82 cm. Hg.
Flowing Air Temp. - 535^{o}R
Resistance Ratio - 1.4
Temp. Correction - + 56 $(ma)^2$
I at Zero velocity - 81.67 ma.

Blower Speed - 910 r.p.m.
Orifice Dia. - 1.544 ins.
Air Density - .0693 lb/ft^3
Vol. Rate of Flow Q_p - .698 ft^3/sec
Average Velocity U_p - 3.275 ft/sec
Reynolds No. Re_p - 9690

1 Dist.from wall ins.	2 Radius r ins.	3 Current I ma.	4 I^2 + T.C. $(ma)^2$	5 $\sqrt{\frac{P}{P_o} U}$ $(ft/sec)^{\frac{1}{2}}$	6 Air Velocity U ft/sec	7 $\frac{U}{U_m}$
.067	3.060	86.87	7603	1.255	1.56	.387
.167	2.960	88.45	7879	1.508	2.24	.557
.267	2.860	89.22	8016	1.631	2.63	.653
.367	2.760	89.75	8111	1.720	2.92	.725
.467	2.660	90.10	8173	1.775	3.12	.774
.627	2.500	90.50	8246	1.840	3.35	.831
.937	2.190	90.75	8291	1.884	3.51	.871
1.247	1.880	91.02	8341	1.928	3.67	.911
1.567	1.560	91.17	8367	1.950	3.76	.933
1.877	1.250	91.30	8391	1.975	3.86	.958
2.187	0.940	91.45	8419	2.000	3.96	.983
2.497	0.630	91.55	8437	2.016	4.01	.995
2.817	0.310	91.57	8442	2.020	4.03	1.000
3.127	0.000	91.57	8442	2.020	4.03	1.000
3.437	0.309	91.52	8432	2.012	4.00	.993
3.757	0.629	91.50	8428	2.006	3.98	.988
4.067	0.939	91.42	8414	1.997	3.94	.978
4.377	1.249	91.32	8396	1.980	3.88	.963
4.687	1.559	91.07	8349	1.936	3.71	.921
5.007	1.879	90.92	8323	1.910	3.61	.896
5.317	2.189	90.72	8286	1.878	3.49	.866
5.627	2.499	90.37	8223	1.821	3.28	.814
5.787	2.659	90.00	8156	1.759	3.06	.760
5.887	2.759	89.62	8087	1.697	2.85	.707
5.987	2.859	89.10	7995	1.611	2.56	.635

TABLE 8D

Profile No. 8 PS.

Room Temp. - 73°F
Barometric Press. - 70.78 cm.Hg.
Flowing Air Temp. - 530°R
Orifice Dia. - 1.544 ins.
Blower Speed - 1050 r.p.m.
W.R.R.C. Rdg. - 61

Air Density - .0698 lbs/ft^3
Vol.Rate of Flow Q_p - 1.210 ft^3/sec
Average Velocity U_p - 5.66 ft/sec
Reynolds No. Re. - 16,900

1 Dist.from wall ins.	2 Radius r ins.	3 Δh ins. alcohol	4 K	5 U ft/sec.	6 $\frac{U}{U_m}$	7 y^+	8 U^+
.153	2.974	.0060	.980	4.77	.678	24.2	14.31
.313	2.814	.0070	.983	5.15	.732	49.8	15.47
.623	2.504	.0078	.985	5.45	.775	98.9	16.38
.933	2.194	.0088	.988	5.80	.825	148	17.40
1.253	1.874	.0100	.990	6.19	.880	199	18.60
1.563	1.564	.0110	.991	6.50	.925	248	19.52
1.873	1.254	.0116	.992	6.67	.949	298	20.02
2.193	.934	.0123	.992	6.87	.977	348	20.62
2.503	.624	.0126	.992	6.97	.991	398	20.92
2.813	.314	.0127	.992	6.99	.993	447	20.99
3.123	.004	.0129	.992	7.04	1.000	-	-
3.443	.315	.0127	.992	6.99	.993	447	20.99
3.753	.625	.0124	.992	6.91	.983	398	20.78
4.063	.935	.0120	.992	6.79	.965	348	20.40
4.373	1.245	.0115	.992	6.65	.945	299	19.97
4.693	1.565	.0108	.991	6.44	.915	248	19.35
5.003	1.875	.0100	.990	6.19	.880	199	18.59
5.313	2.185	.0091	.989	5.90	.839	149	17.70
5.633	2.505	.0080	.986	5.53	.786	98.7	16.60
5.943	2.815	.0069	.983	5.12	.728	49.5	15.39
6.103	2.975	.0059	.980	4.73	.673	24.2	14.20

TABLE 9D

Profile No. 8 HW.

Date - Nov. 16 Resistance Ratio - 1.4
Room Temp. - 72 °F H.W. rdgs. based on calibration no. 1.
Barometric Press. - 70.05 cm.Hg. Temp. Correction - + 11 $(ma)^2$
Flowing Air Temp. - 539 °R
Orifice Dia. - 1.544 ins.
Blower Speed - 1050 r.p.m.
W.R.R.C. Rdg. - 61

1 Dist.from wall ins.	2 Radius r ins.	3 Current I ma.	4 I^2 + T.C. $(ma)^2$	5 $\sqrt{\frac{P}{P_o}}\ U$ $(ft/sec)^{\frac{1}{2}}$	6 Air Velocity U ft/sec	7 $\frac{U}{U_m}$
.067	3.060	91.17	8322	1.92	3.69	.521
.167	2.960	92.67	8598	2.17	4.71	.665
.267	2.860	92.90	8641	2.21	4.88	.690
.367	2.760	93.40	8735	2.30	5.29	.747
.467	2.660	93.52	8756	2.32	5.38	.760
.627	2.500	93.82	8812	2.36	5.57	.787
.937	2.190	94.40	8922	2.47	6.10	.861
1.247	1.880	94.67	8973	2.51	6.30	.890
1.567	1.560	94.77	8992	2.53	6.40	.904
1.877	1.250	95.00	9036	2.57	6.60	.932
2.187	0.940	95.25	9083	2.62	6.86	.969
2.497	0.630	95.35	9102	2.63	6.92	.978
2.817	0.310	95.40	9113	2.64	6.97	.985
3.127	0.000	95.50	9131	2.66	7.08	1.000
3.437	0.309	95.47	9124	2.64	6.97	.985
3.757	0.629	95.37	9106	2.64	6.97	.985
4.067	0.939	95.30	9092	2.62	6.86	.969
4.377	1.249	95.05	9044	2.58	6.66	.941
4.687	1.559	94.77	8993	2.53	6.40	.904
5.007	1.879	94.62	8964	2.51	6.30	.890
5.317	2.189	94.35	8912	2.46	6.05	.855
5.627	2.499	93.77	8804	2.36	5.57	.787
5.787	2.659	93.50	8752	2.31	5.34	.755
5.887	2.759	93.45	8745	2.31	5.34	.755
5.987	2.859	93.02	8663	2.23	4.97	.703

TABLE 10D

Profile No. 8 HF.

Date - Dec. 15
Room Temp. - 73°F
Barometric Press. - 70.95 cm.Hg.
Flowing Air Temp. - 540°R
Orifice Dia. - 1.544 ins.
Blower Speed - 1050 r.p.m.
W.R.R.C. Rdg. - 61

Resistance Ratio - 1.1
H.F. rdgs. based on calibration no. 2.

1 Dist. from wall ins.	2 Radius r ins.	3 Current I ma.	4 I^2 $(ma)^2$	5 $\sqrt{\frac{P}{P_o}}\,U$ $(ft/sec)^{\frac{1}{2}}$	6 Air Velocity U ft/sec	7 $\frac{U}{U_m}$
.125	3.002	35.00	1225	2.15	4.56	.658
.315	2.812	35.22	1241	2.28	5.14	.741
.625	2.502	35.40	1253	2.37	5.55	.801
.935	2.192	35.47	1258	2.41	5.74	.829
1.255	1.872	35.62	1268	2.48	6.08	.878
1.565	1.562	35.77	1279	2.57	6.52	.941
1.875	1.252	35.80	1281	2.58	6.58	.950
2.195	.932	35.82	1283	2.60	6.68	.964
2.505	.622	35.87	1287	2.63	6.83	.986
2.815	.312	35.92	1290	2.65	6.93	1.000
3.125	.002	35.92	1290	2.65	6.93	1.000
3.445	.317	35.92	1290	2.65	6.93	1.000
3.755	.627	35.90	1289	2.64	6.88	.993
4.065	.937	35.85	1285	2.61	6.73	.970
4.375	1.247	35.77	1279	2.57	6.52	.941
4.695	1.567	35.75	1278	2.56	6.47	.934
5.005	1.877	35.70	1274	2.53	6.32	.911
5.315	2.187	35.62	1268	2.48	6.07	.876
5.635	2.507	35.45	1257	2.40	5.69	.820
5.945	2.817	35.17	1237	2.24	4.69	.716
6.130	3.002	34.85	1214	2.07	4.22	.609

TABLE 11D

Profile No. 9 PS.

Room Temp. - 72°F
Barometric Press. - 70.65 cm.Hg.
Flowing Air Temp. - 529°F
Orifice Dia. - 1.544 ins.
Blower Speed - 1050 r.p.m.
W.R.R.C. Rdg. - 67

Air Density - .0698 lbs/ft^3
Vol.Rate of Flow Q_p - 1.308 ft^3/sec
Average Velocity $\bar{U}_p$ - 6.13 ft/sec
Reynolds No. Re. - 18,300

1 Dist.from wall ins.	2 Radius r ins.	3 Δh ins. alcohol	4 K	5 Air Velocity U ft/sec	6 $\frac{U}{U_m}$	7 y^+	8 U^+
.153	2.974	.0065	.982	4.96	.659	25.9	13.90
.313	2.814	.0080	.986	5.53	.734	53.3	15.49
.623	2.504	.0095	.989	6.04	.801	106.0	16.92
.933	2.194	.0105	.991	6.35	.843	158.5	17.80
1.253	1.874	.0115	.992	6.66	.884	213	18.65
1.563	1.564	.0124	.992	6.91	.917	266	19.35
1.873	1.254	.0132	.992	7.12	.945	319	19.94
2.193	.934	.0137	.992	7.26	.964	373	20.33
2.503	.624	.0142	.991	7.38	.980	425	20.68
2.813	.314	.0146	.991	7.49	.994	479	21.00
3.123	.004	.0148	.991	7.54	1.000	-	-
3.443	.315	.0146	.991	7.49	.994	479	21.00
3.753	.625	.0142	.991	7.38	.980	425	20.68
4.063	.935	.0137	.992	7.26	.964	373	20.33
4.373	1.245	.0131	.992	7.09	.940	320	19.86
4.693	1.565	.0124	.992	6.91	.917	266	19.35
5.003	1.875	.0115	.992	6.66	.884	213	18.65
5.313	2.185	.0105	.991	6.35	.843	160.0	17.80
5.633	2.505	.0093	.989	5.96	.791	105.9	16.70
5.943	2.815	.0080	.986	5.53	.734	53.0	15.49
6.103	2.975	.0064	.982	4.93	.654	25.9	13.80

TABLE 12D

Profile No. 10 PS.

Room Temp. - 75°F
Barometric Press. - 70.78 cm.Hg.
Flowing Air Temp. - 533°R
Orifice Dia. - 1.544 ins.
Blower Speed - 1050 r.p.m.
W.R.R.C. Rdg. - 78

Air Density - .0695 lbs/ft^3
Vol.Rate of Flow Q_p - 1.512 ft^3/sec
Average Velocity $\bar{U}_p$ - 7.09 ft/sec
Reynolds No. Re. - 21,000

1 Dist.from wall ins.	2 Radius r ins.	3 Δh ins. alcohol	4 K	5 Air Velocity U ft/sec	6 $\frac{U}{U_m}$	7 y^+	8 U^+
.153	2.947	.0087	.988	5.78	.666	29.4	14.22
.313	2.814	.0105	.990	6.35	.731	60.3	15.62
.623	2.504	.0125	.992	6.95	.800	120	17.10
.933	2.194	.0141	.991	7.37	.849	180	18.13
1.253	1.874	.0153	.991	7.67	.884	241	18.89
1.563	1.564	.0164	.990	7.95	.916	301	19.58
1.873	1.254	.0174	.989	8.19	.943	361	20.18
2.193	.934	.0183	.988	8.39	.966	422	20.65
2.503	.624	.0190	.988	8.55	.985	482	21.05
2.813	.314	.0194	.987	8.63	.994	542	21.25
3.123	.004	.0196	.987	8.68	1.000	-	-
3.443	.315	.0194	.987	8.63	.994	542	21.25
3.753	.625	.0190	.988	8.55	.985	482	21.05
4.063	.935	.0183	.988	8.39	.966	422	20.65
4.373	1.245	.0174	.989	8.19	.943	362	20.18
4.693	1.565	.0164	.990	7.95	.916	301	19.58
5.003	1.875	.0153	.991	7.67	.884	241	18.89
5.313	2.185	.0141	.991	7.37	.849	181	18.13
5.633	2.505	.0123	.992	6.88	.793	120	16.95
5.943	2.815	.0103	.990	6.30	.725	60.1	15.50
6.103	2.975	.0083	.987	5.65	.650	29.4	13.90

TABLE 13D

Profile No. 11 PS.

Room Temp. - 72°F
Barometric Press. - 70.73 cm.Hg.
Flowing Air Temp. - 531°R
Orifice Dia. - 1.544 ins.
Blower Speed - 1325 r.p.m.
W.R.R.C. Rdg. - 87

Air Density - .0697 lbs/ft^3
Vol. Rate of Flow Q_p - 1.740 ft^3/sec
Average Velocity $\bar{U}_p$ - 8.06 ft/sec
Reynolds No. Re. - 24,000

1 Dist.from wall ins.	2 Radius r ins.	3 Δh ins. alcohol	4 K	5 Air Velocity U ft/sec	6 $\frac{U}{U_m}$	7 y^+	8 U^+
.153	2.974	.0118	.992	6.74	.685	32.9	14.88
.313	2.814	.0129	.992	7.04	.716	67.6	15.53
.623	2.504	.0160	.990	7.84	.797	134	17.30
.933	2.194	.0183	.988	8.38	.852	201	18.50
1.253	1.874	.0200	.987	8.75	.890	270	19.30
1.563	1.564	.0214	.987	9.05	.921	337	19.99
1.873	1.254	.0228	.986	9.34	.950	405	20.60
2.193	.934	.0234	.986	9.44	.960	473	20.82
2.503	.624	.0244	.986	9.65	.982	540	21.30
2.813	.314	.0251	.986	9.80	.997	608	21.63
3.123	.004	.0253	.986	9.83	1.000	-	-
3.443	.315	.0251	.986	9.80	.997	608	21.63
3.753	.625	.0244	.986	9.65	.982	540	21.30
4.063	.935	.0238	.986	9.53	.970	473	21.02
4.373	1.245	.0227	.986	9.31	.947	406	20.55
4.693	1.565	.0213	.987	9.04	.920	337	19.95
5.003	1.875	.0199	.987	8.73	.888	270	19.28
5.313	2.185	.0180	.989	8.30	.845	203	18.32
5.633	2.505	.0160	.990	7.84	.797	134	17.30
5.943	2.815	.0134	.992	7.18	.730	67.4	15.86
6.103	2.975	.0119	.992	6.77	.689	32.9	14.95

TABLE 14D

Profile No. 11 HW.

Date - Nov. 17
Room Temp. - 72°F
Barometric Press.- 70.16 cm.Hg.
Flowing Air Temp.- 542°R
Orifice Dia. - 1.544 ins.
Blower Speed - 1325 r.p.m.
W.R.R.C. Rdg. - 87

Resistance Ratio - 1.4
H.W. rdgs. based on calibration no.2.
Temp. Correction - -22 $(\text{ma})^2$

1 Dist.from wall ins.	2 Radius r ins.	3 Current I ma.	4 $I^2 + T.C.$ $(\text{ma})^2$	5 $\sqrt{\frac{P}{P_o}}\ U$ $(\text{ft/sec})^{\frac{1}{2}}$	6 Air Velocity U ft/sec	7 $\frac{U}{U_m}$
.067	3.060	93.77	8771	2.29	5.23	.536
.167	2.960	95.30	9060	2.55	6.49	.665
.267	2.860	95.70	9135	2.61	6.80	.696
.367	2.760	96.17	9227	2.69	7.22	.740
.467	2.660	96.45	9280	2.74	7.49	.766
.627	2.500	96.85	9358	2.81	7.88	.807
.937	2.190	97.30	9445	2.89	8.33	.853
1.247	1.880	97.70	9523	2.96	8.73	.894
1.567	1.560	97.97	9575	3.00	8.98	.920
1.877	1.250	98.20	9621	3.04	9.22	.944
2.187	0.940	98.27	9635	3.06	9.34	.956
2.497	0.630	98.60	9700	3.12	9.70	.994
2.817	0.310	98.65	9710	3.12	9.70	.994
3.127	0.000	98.70	9720	3.13	9.77	1.000
3.437	0.309	98.65	9710	3.12	9.73	.994
3.757	0.629	98.47	9673	3.09	9.55	.975
4.067	0.939	98.27	9636	3.06	9.36	.956
4.377	1.249	98.25	9631	3.05	9.30	.950
4.687	1.559	98.07	9596	3.02	9.12	.932
5.007	1.879	97.57	9498	2.94	8.64	.883
5.317	2.189	97.32	9450	2.89	8.35	.853
5.627	2.499	96.82	9352	2.80	7.84	.801
5.787	2.659	96.57	9303	2.76	7.62	.778
5.887	2.759	96.22	9235	2.70	7.29	.744
5.987	2.859	95.70	9135	2.61	6.81	.696

TABLE 15D

Profile No. 12 PS.

Room Temp. - 73^{o}F
Barometric Press.- 70.94 cm.Hg.
Flowing Air Temp.- 533^{o}R
Orifice Dia. - 1.544 ins.
Blower Speed - 1350 r.p.m.
W.R.R.C. Rdg. - 103

Air Density - .0697 lb/ft^3
Vol. Rate of Flow Q_p - 1.878 ft^3/sec
Average Velocity U_p - 8.80 ft/sec
Reynolds No. Re. - 26,200

1 Dist. from wall ins.	2 Radius r ins.	3 Δh ins. alcohol	4 K	5 Air Velocity U ft/sec	6 $\frac{U}{U_m}$	7 y^+	8 U^+
.153	2.974	.0127	.992	6.99	.644	35.6	14.27
.313	2.814	.0158	.991	7.80	.719	73.1	15.90
.623	2.504	.0192	.988	8.58	.791	145	17.51
.933	2.194	.0218	.986	9.13	.842	218	18.62
1.253	1.874	.0241	.986	9.60	.885	292	19.60
1.563	1.564	.0261	.986	10.00	.922	365	20.40
1.873	1.254	.0276	.987	10.29	.948	437	21.00
2.193	.934	.0288	.988	10.50	.968	511	21.42
2.503	.624	.0297	.989	10.68	.984	585	21.77
2.813	.314	.0303	.990	10.79	.994	657	22.00
3.123	.004	.0306	.990	10.85	1.000	-	-
3.443	.315	.0303	.990	10.79	.994	657	22.00
3.753	.625	.0297	.989	10.68	.984	585	21.77
4.063	.935	.0288	.988	10.50	.968	511	21.42
4.373	1.245	.0276	.987	10.29	.948	439	21.00
4.693	1.565	.0261	.986	10.00	.922	365	20.40
5.003	1.875	.0241	.986	9.60	.885	292	19.60
5.313	2.185	.0218	.986	9.13	.842	220	18.62
5.633	2.505	.0192	.988	8.58	.791	145	17.51
5.943	2.815	.0156	.991	7.74	.713	72.9	15.79
6.103	2.975	.0127	.992	6.99	.644	35.6	14.27

TABLE 16D

Profile No. 13 PS.

Room Temp. - 72°F
Barometric Press.- 69.35 cm.Hg.
Flowing Air Temp.- 535°R
Orifice Dia. - 1.544 ins.
Blower Speed - 1570 r.p.m.
W.R.R.C. Rdg. - 116

Air Density - .0679 lbs/ft^3
Vol.Rate of Flow Q_p -2.260 ft^3/sec
Average Velocity $\bar{U}_p$ -10.60 ft/sec
Reynolds No. Re. -30,700

1 Dist.from wall ins.	2 Radius r ins.	3 Δh ins.alcohol	4 K	5 Air Velocity U ft/sec	6 $\frac{U}{U_m}$	7 y^+	8 U^+
.153	2.974	.0197	.987	8.81	.676	40.9	15.22
.313	2.814	.0228	.986	9.46	.726	84.1	16.35
.623	2.504	.0272	.987	10.33	.794	167	17.85
.933	2.194	.0305	.990	10.95	.841	250	18.91
1.253	1.874	.0331	.994	11.45	.880	336	19.80
1.563	1.564	.0358	.995	11.90	.915	420	20.58
1.873	1.254	.0380	.997	12.28	.944	503	21.22
2.193	.934	.0393	.998	12.49	.960	589	21.60
2.503	.624	.0406	.999	12.70	.976	672	21.96
2.813	.314	.0421	1.000	12.93	.995	756	22.37
3.123	.004	.0426	1.000	13.01	1.000	-	-
3.443	.315	.0419	1.000	12.90	.992	756	22.30
3.753	.625	.0410	.999	12.77	.982	672	22.08
4.063	.935	.0396	.998	12.55	.965	589	21.70
4.373	1.245	.0381	.997	12.29	.945	505	21.23
4.693	1.565	.0356	.995	11.87	.913	420	20.52
5.003	1.875	.0333	.994	11.47	.881	336	19.82
5.313	2.185	.0303	.990	10.93	.840	253	18.90
5.633	2.505	.0270	.987	10.30	.791	167	17.80
5.943	2.815	.0227	.986	9.44	.724	83.8	16.30
6.103	2.975	.0193	.987	8.72	.670	40.9	15.08

TABLE 17D

Profile No. 13 HW.

Date - Nov. 20
Room Temp. - 72°F
Barometric Press.- 69.87 cm.Hg.
Flowing Air Temp.- 546°R
Orifice Dia. - 1.544 ins.
Blower Speed - 1570 r.p.m.
W.R.R.C. Rdg. - 116

Resistance Ratio - 1.4
H.W.rdgs. based on calibration no.3.
Temp. Correction - -67 $(ma)^2$

1 Dist.from wall ins.	2 Radius r ins.	3 Current I ma.	4 I^2 + T.C. $(ma)^2$	5 $\sqrt{\frac{P}{P_0}U}$ $(ft/sec)^{\frac{1}{2}}$	6 Air Velocity U ft/sec	7 $\frac{U}{U_m}$
.067	3.060	95.30	9015	2.60	6.77	.522
.167	2.960	97.00	9342	2.91	8.48	.654
.267	2.860	97.55	9448	3.02	9.13	.704
.367	2.760	97.90	9516	3.08	9.51	.733
.467	2.660	98.27	9590	3.15	9.94	.765
.627	2.500	98.55	9645	3.20	10.26	.790
.937	2.190	99.17	9768	3.32	11.04	.851
1.247	1.880	99.45	9823	3.37	11.38	.878
1.567	1.560	99.95	9923	3.47	12.06	.930
1.877	1.250	100.10	9953	3.49	12.20	.941
2.187	0.940	100.35	10003	3.54	12.55	.967
2.497	0.630	100.55	10043	3.58	12.84	.990
2.817	0.310	100.62	10057	3.59	12.91	.996
3.127	0.000	100.67	10067	3.60	12.98	1.000
3.437	0.309	100.62	10057	3.59	12.91	.996
3.757	0.629	100.47	10027	3.57	12.76	.984
4.067	0.939	100.40	10013	3.55	12.62	.974
4.377	1.249	100.05	9943	3.48	12.13	.936
4.687	1.559	99.87	9907	3.45	11.92	.920
5.007	1.879	99.50	9833	3.38	11.44	.882
5.317	2.189	99.25	9783	3.33	11.11	.856
5.627	2.499	98.55	9645	3.20	10.26	.790
5.787	2.659	98.22	9580	3.14	9.88	.761
5.887	2.759	97.95	9527	3.09	9.57	.737
5.987	2.859	97.62	9463	3.03	9.19	.708

NOMENCLATURE

f	Blasius friction factor = $0.079\ Re^{-\frac{1}{4}}$
Δh	dynamic head, read by means of micromanometer
I	heating current to wire
K	pitot-static tube factor
P	absolute pressure
P_o	reference pressure (70 cm.Hg.)
Q_o	volumetric rate of flow of air at air stream conditions of temperature and pressure, calculated from the orifice pressure drop.
Q_p	volumetric rate of flow of air at air stream conditions of temperature and pressure, estimated by integration of the velocity profile
R	pipe radius
Re	Reynolds number
r	radius to measuring point
T.C.	temperature correction to hot wire response
U	mean air velocity at measuring point
U_m	mean flow velocity at pipe axis
$\bar{U}_o$	average velocity of flow in pipe obtained from Q_o
$\bar{U}_p$	average velocity of flow in pipe obtained from Q_p
U^+	$\frac{U}{U_*}$
U_*	friction velocity = $U\sqrt{\frac{f}{2}}$
y	$R - r$
y^+	$\frac{y\ U_*\ \rho}{\mu}$
ρ	air density at stream conditions of temperature and pressure
μ	air viscosity

APPENDIX E

METHODS OF CALCULATION

METHODS OF CALCULATION

1. Mean velocity from pitot-static tube readings

Mean velocity was calculated using pitot-static tube equation 1.

$$U = \sqrt{\frac{2Kg_c \Delta P}{\rho}} = \sqrt{\frac{8.40\ Kg_c \Delta h}{\rho}} \qquad (1)$$

where: U = air velocity (ft./sec.)

K = pitot-static tube factor obtained from appendix A

ΔP = dynamic pressure (lb_f/ft^2)

ρ = air density (lb_m/ft^3) obtained using the perfect gas law

Δh = micromanometer reading (inches)

g_c = gravitational constant (lb_m/lb_f. $ft./sec^2$)

2. Mean velocity from the hot-wire or hot-film readings

Mean velocity was calculated using the hot-wire equation B8:

$$I^2 + 0.9 \left[\frac{T_o - T}{T_o}\right] I_o^2 = A \sqrt{\frac{P}{P_o}}\, U + B \qquad (B8)$$

where: I = heating current required (ma.)

I_o = heating current required at zero air velocity (ma.)

T_o = reference temperature ($540^\circ R$)

T = flowing air temperature ($^\circ R$)

P = static pressure in test section (cm. Hg.)

P_o = reference pressure (70 cm. Hg.)

A and B = calibration constants

It should be noted that equation B8 contains the temperature correction term:

$$TC = 0.9 \left[\frac{T_o - T}{T_o}\right] I_o^2$$

This term was omitted when estimating velocities from hot-film readings.

3. Least squares analysis to obtain calibration constants A and B.

By assuming the error to be in current measurement and making a least squares analysis it can be shown that:

$$A = \frac{N\sum_i I_i\sqrt{u_i} - \sum_i \sqrt{u_i}\,\sum_i I_i^2}{N\sum_i u_i - (\sum_i \sqrt{u_i})^2} \tag{E1}$$

and:

$$B = \frac{\sum_i I_i^2}{N} - A\,\frac{\sum_i \sqrt{u_i}}{N} \tag{E2}$$

where:

A and B = calibration constants

I_i = temperature corrected heating current (ma.)

U_i = pressure corrected velocity i.e. $\sqrt{\frac{PU}{P_o}}$ (ft./sec.)

N = number of calibration points

4. The integration of velocity profiles to obtain flow rate.

Flow rate was estimated by use of the equation:

$$Q_p = \frac{2\pi}{144}\int_0^R Urdr \tag{E3}$$

where: Q_p = volume rate of flow (ft.^{3}/sec.)

U = point velocity (ft./sec.)

r = radius (ins.)

The integration involved was carried out graphically.

5. Flow rate from the orifice pressure drop.

Flow rate was computed by means of the orifice equation:

$$Q_o = C_o A_o \sqrt{\frac{2g_c \Delta P_o}{\rho}} = 0.008805\ C_o \sqrt{\frac{\Delta h}{\rho}} \qquad \text{(E4)}$$

where: Q_o = volumetric rate of flow of air at upstream conditions of temperature and pressure (ft.^{3}/sec.)

A_o = orifice cross-sectional area = .0007668 ft^2

C_o = orifice coefficient

ΔP_o = orifice pressure drop $\frac{lb_f}{ft^2}$

ρ = air density $\frac{lb_m}{ft^3}$

Δh = manometer reading (cm. of H_2O)

6. Friction velocity.

The friction velocity was calculated using the equation:

$$U^* = U\sqrt{\frac{f}{2}} \qquad \text{(E5)}$$

where: U^* = friction velocity (ft./sec.)

U = air velocity (ft./sec.)

f = friction factor

The friction factor f was obtained from the Blasius friction factor equation:

$$f = 0.079\ Re^{-\frac{1}{4}} \qquad \text{(E6)}$$

where: Re = Reynolds number

7. Error in velocity measurement with the pitot-static tube.

By an error analysis it can be shown that:

Percentage error in velocity = $\frac{1}{2}$ percentage error in Δh

where: Δh = micromanometer reading

This formula was used to estimate the error in velocity measurements with the pitot-static tube.

8. Error in velocity measurement with the hot-wire and hot-film probes.

The formula used for the estimation of error involved in measurement of mean velocity with the hot-wire and hot-film probes was derived as follows:

Let the error in I be $\pm \Delta I$,

$$\text{Percentage error in } I^2 = 2 \text{ x percentage error in } I$$

$$= 2 \times \frac{\Delta I}{I} \times 100 \quad \text{-----------} \quad (E7)$$

$$\therefore \text{ Error in } I^2 = 2 \left[\frac{\Delta I}{I}\right] I^2 \quad \text{-----------} \quad (E8)$$

It is obvious that:

$$\text{Error in } I^2 - b = \text{Error in } I^2 \quad \text{-----------} \quad (E9)$$

From equation E8:

$$\text{Error in } I^2 - b = 2.\Delta I.I \quad \text{-----------} \quad (E9)$$

$$\text{Percentage error in } I^2 - b = \frac{2I.\Delta I}{I^2 - b} \times 100 \quad \text{-----------} \quad (E11)$$

$$\text{Percentage error velocity} = 2 \text{ x percentage error in } I^2 - b$$

$$= 4 \frac{I.\Delta I}{I^2 - b} \times 100 \quad \text{-----------} \quad (E12)$$

Equation E12 was used to make estimations of percentage error in velocity measurement.

9. The trial and error procedure to establish calibration of HWP-A hot-wire probe in the low velocity range.

(a) The flow rate was established for each profile from the orifice pressure drop. Calculation of the flow rate Q_o was made using the orifice flow equation E4. The average velocity $\bar{U}_o$ in the test pipe was obtained from this flow rate.

(b) A value of the ratio $\bar{U}/U_m$ was assumed and the corresponding value of centre line velocity U_{mo} calculated thus:

$$U_{mo} = \bar{U}_o \times \frac{U_m}{\bar{U}}$$

where: $\bar{U}$ = average velocity of flow in pipe

U_m= velocity at the axis of the pipe

(c) The value of I^2 (temperature corrected) for the centre of each profile was plotted against the appropriate value of U_{mo} and an approximate calibration curve drawn.

(d) Using the approximate calibration curve the profiles were established and integrated to obtain the flow rate Q_p as described in section E4. The average velocity $\bar{U}_p$ in the test pipe for this flow rate was calculated and used to obtain the ratio $\bar{U}_p/U_{mp}$ for each profile, U_{mp} being the velocity at the pipe axis estimated from the approximated calibration curve.

(e) These new ratios $\bar{U}_p/U_{mp}$ were substituted for the assumed values of $\bar{U}/U_m$ in step (b) and a second approximation of the calibration curve made. Steps (c) and (d) were repeated to test the accuracy of this calibration and to establish more accurate values of $\bar{U}/U_m$.

(f) Trials were continued until the changes in the ratios $\bar{U}_p/U_{mp}$ from trial to trial became insignificant. The final trial was accepted as representing the calibration of the probe in the low velocity range.

APPENDIX F

CALIBRATION OF THE ORIFICE

CALIBRATION OF THE ORIFICE

A 3/8 inch diameter orifice was calibrated in the meter run against a displacement meter. The displacement meter itself had been previously calibrated against a gas holder over the range of air flow 0.07 to 0.20 cubic feet per second. The calibration factor over this range was found to be a constant given by:-

$$\frac{\text{True Volume}}{\text{Meter Reading}} = 0.995$$

Air for the orifice calibration was supplied by the blower running at a speed of 910 r.p.m. After passing through the meter run it was exhausted to atmosphere through the displacement meter. The pressure drop across the orifice was measured using a U-tube manometer containing distilled water. Air temperature was recorded using the thermocouple and Brown temperature recorder and the static pressure upstream of the orifice was measured using a second U-tube manometer containing distilled water.

Readings of orifice pressure drop, flowing air temperature and absolute pressure upstream of the orifice were taken at various air mass flow rates obtained by changing the setting of the weight rate recorder controller. The values of the mass flow rates were obtained by measuring the time required for a known volume of air to pass through the displacement meter.

The orifice coefficient C_o was calculated using the equation:

$$Q_o = C_o A_o \sqrt{\frac{2g_c \Delta P_o}{\rho}} \qquad \text{(E4)}$$

where: Q_o = volumetric rate of flow of air at upstream conditions of temperature and pressure

C_o = orifice coefficient

A_o = cross-sectional area of the orifice opening

$\triangle P_o$ = pressure drop across the orifice

ρ = air density at upstream conditions

The results of the calibration are given in table 1F. The average value of the orifice coefficient C_o for the range 0.07 to 0.20 cubic feet per second was found to be 0.828.

TABLE 1F

Calibration of 3/8 inch diameter Sharp Edged Orifice

Test No.	Flowing Air Temperature ^oR	Static Upstream Pressure inches H_2O	Orifice Pressure drop cm. H_2O	Volume passed through Displacement Meter $(feet)^3$	Time (secs)	C_o
1F	539	377.4	6.5	5.0	70.5	0.823
2F	539	377.6	11.1	5.0	53.6	0.828
3F	539	377.9	14.8	5.0	46.5	0.826
4F	539	378.0	18.6	5.0	41.7	0.822
5F	539	378.1	22.0	5.0	37.7	0.837
6F	543	378.5	28.1	10.0	66.9	0.831
7F	547	378.7	33.7	10.0	61.3	0.826
8F	549	379.0	41.1	10.0	55.1	0.831
9F	551	379.5	52.4	10.0	48.9	0.831

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